AD 715043

NASA TECHNICAL NOTE

NASA TN D-6098

NASA TN D-6098

A COMPARISON OF AIRCRAFT AND GROUND VEHICLE STOPPING PERFORMANCE ON DRY, WET, FLOODED, SLUSH-, SNOW-, AND ICE-COVERED RUNWAYS

Final Report on Project Combat Traction, a Joint USAF-NASA Program

by

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1970

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No
NASA TN D-6098		

4. Title and Subtitle	5. Report Date
A COMPARISON OF AIRCRAFT AND GROUND VEHICLE STOPPING PERFORMANCE ON DRY, WET, FLOODED, SLUSH-, SNOW-, AND ICE-COVERED RUNWAYS	November 1970
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No
Thomas J. Yager, W. Pelham Phillips, Walter B. Horne, and Howard C. Sparks	L-7565
	10. Work Unit No
9. Performing Organization Name and Address	126-61-12-05
NASA Langley Research Center, Hampton, Va. 23365 USAF Wright-Patterson Air Force Base, Ohio 45433	11. Contract or Grant No
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Note
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Appendix D by R. W. Sugg of British Ministry of Aircraft Supply

16. Abstract

A joint USAF-NASA research program has studied the stopping performance of an instrumented C-141A four-engine jet transport and several instrumented ground vehicles on 50 runways in the United States and Europe under dry, wet, flooded, slush, snow, and ice conditions. It is shown that measurement of the stopping distance of a diagonal-braked ground vehicle provides a meaningful measure of the slipperiness of a wet runway, and permits accurate prediction of the stopping distance of an aircraft under varied runway slipperiness conditions as well as a means for realistic calculation of crosswind limitations. It is also shown that aircraft stopping performance on a wet runway can be considerably improved either by grooving the runway or by use of a porous surface course.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Runway surface treatments Aircraft-ground vehicle stopping performance Runway slipperiness due to adverse weather	Unclassified – Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	196	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

A joint USAF-NASA research program has studied the stopping performance of an instrumented C-141A four-engine jet transport and several instrumented ground vehicles on 50 runways in the United States and Europe under dry, wet, flooded, slush, snow, and ice conditions. It is shown that measurement of the stopping distance of a diagonal-braked ground vehicle provides a meaningful measure of the slipperiness of a wet runway, and permits accurate prediction of the stopping distance of an aircraft under varied runway slipperiness conditions as well as a means for realistic calculation of crosswind limitations. It is also shown that aircraft stopping performance on a wet runway can be considerably improved either by grooving the runway or by use of a porous surface course.

INTRODUCTION

Wet-runway operating problems became of primary concern with the introduction of jet aircraft since their landing speeds are usually well above the hydroplaning speed of their tires. In addition, improved flight instruments and instrument landing systems have led to more landings being made under adverse weather conditions. The increased landing speeds coupled with more landings being made on wet runways have resulted in more landing accidents occurring because of the lack of effective braking action. This experience with both military and civil jet aircraft operation indicates that the presently used

performance prediction methods for aircraft take-off and landing accountability on wet or slippery runways are deficient in several respects.

For certification of piston-engine category aircraft for civil operation, performance on dry runways is determined and FAA regulations increase the dry landing distances thus obtained by a factor of 1.67 to provide a safety margin for operation on dry runways, and to provide for the increase in stopping distance required on a wet runway. In January 1966, the FAA instituted the 15-percent rule which increased this factor to 1.92 for jet-turbine-category aircraft operation on wet runways; thus, recognition was made of the fact that jet-engine-powered aircraft were experiencing more difficulty in stopping on wet or slippery runways than the piston-engine aircraft. This civil regulatory approach for wet-runway accountability does not differentiate between runways of different slipperiness and does not account for the loss of directional control due to reduction in sideways traction.

The U.S. Air Force uses the RCR or runway condition reading system to account for wet or slippery runway conditions. RCR numbers are obtained by making maximum braking measurements on the runway with an airport ground vehicle employing a James brake decelerometer at speeds of 20 to 30 miles per hour. The flight manual of every aircraft in the U.S. Air Force inventory contains take-off and landing distance charts based on RCR numbers. Also given are crosswind limitations based on the same RCR numbers. The main problem associated with the RCR system has been that the low-speed measurements of runway slipperiness made by the ground vehicle cannot be uniquely related to the actual slipperiness experienced by the aircraft at the higher speeds of the landing roll, especially on wet runways. As a result, the RCR system can considerably underestimate the actual aircraft landing distance on a wet runway. For the same reason, an unconservative crosswind limitation can be given the pilot for a landing or take-off.

For the past decade, the U.S. Air Force (USAF) and National Aeronautics and Space Administration (NASA) have been cooperating extensively on research of aircraft skidding problems on wet and slippery runways. The USAF furnished aircraft tires, landing gears, wheels, and complete aircraft for study by scientists at specially equipped research facilities of the NASA Langley Research Center and Wallops Station. From this effort, along with outstanding cooperation and assistance of the FAA, NTSB, ATA, and ALPA in this country, and the Ministry of Public Works and Roads, Road Research Laboratories, and Ministry of Aviation Supply in England, many studies were generated which greatly increased the understanding of hydroplaning and other skidding factors.

During the late fifties and early sixties, Langley Research Center conducted research on the landing loads track on full-size aircraft tires which disclosed a significant loss of traction and complete wheel spin-down due to hydroplaning. These results

were confirmed with flight tests. One important early result of this work was the development of the slush drag and dynamic hydroplaning equations. Extensive tests at the landing loads track showed how tire groove patterns and depth affected the ability of the tire to develop friction on wet and flooded surfaces. Friction was found to increase with an increase in the number and depth of grooves. The studies, however, showed the groove patterns to be insignificant in affecting friction when less than approximately 1/16 inch of groove depth remained. In this same period, joint testing by the FAA and NASA of an instrumented four-engine jet transport also investigated hydroplaning in terms of aircraft slush-drag reduction and unbraked wheel spindown. Also, a study of aircraft skidding accidents had revealed that in many cases, there were elliptical areas of reverted rubber on the tire tread. It was evident that the tire had undergone a locked-wheel skid of a lengthy duration. Tests at the NASA landing loads track confirmed the fact that extremely low values of friction occurred when tires contained reverted-rubber patches. Another type of hydroplaning was that associated with thin fluid films between pavement and tire and designated as viscous hydroplaning.

The research indicated that measures other than tire-tread design would have to be taken to solve the total runway hydroplaning problem, which was designated in three types as dynamic hydroplaning, viscous skidding, and reverted-rubber skidding. One approach to solve the problem of low friction under dynamic hydroplaning conditions was to direct a stream of high-pressure air in front of the tire to displace the water on the runway. Subsequent tests made by NASA on their landing loads track and the Douglas Aircraft Company on a DC-7 showed a significant improvement in friction under flooded conditions; however, under wet and damp conditions, viscous and reverted-rubber skidding was still experienced.

It was obvious that the solution to the problem of skidding would not come from tire or aircraft improvement alone. Attention was then focused on the pavement surface. A British study revealed that transverse grooves in the pavement surface provided significant improvement in the traction of a problem runway. Tests on similarly grooved surfaces at the NASA landing loads track under flooded, wet, and damp conditions showed that grooved surfaces greatly alleviated dynamic hydroplaning, viscous skidding, and reverted-rubber skidding.

The next step was to construct a research runway at the NASA Wallops Station. Tests were conducted with three aircraft and several friction-measuring vehicles. Results of these tests and tests at Langley Research Center indicated that grooves in the runway surfaces did indeed improve landing characteristics. (See ref. 1.) As a result, surfaces of runways at several Air Force and civil airports were grooved. The data from the test track and the short test sections at Wallops Station, however, left many questions unanswered as to the relative merits of the different surfaces and surface treatments for a full-length runway.

Project Combat Traction was initiated as a joint U.S. Air Force-NASA project consisting of two parts: (a) Full-stop brake tests were made by an instrumented C-141A aircraft, an RCR test vehicle, and a diagonal-braked test vehicle on civil and military runways in the United States and Europe under dry, artificially wet, natural rain, ice, and snow conditions. Included in the European program were tests conducted jointly with the British Ministry of Aviation Supply on Royal Air Force (RAF) and Royal Navy (RN) Bases using a Mu-meter and a Miles engineering skid trailer. (b) Limited brake tests were conducted on the landing research runway at NASA Wallops Station, with the C-141A to correlate the results with those of similar tests previously conducted on an F-4D and a Convair 990A, and Beech Queen Aire. Most of the research described in the introduction is contained in references 1 to 15.

These programs were designed to meet the following research objectives as specified in reference 16:

(a) Establish and validate a means for predicting aircraft stopping distance for various surfaces by use of a ground vehicle as a means of assessing surface condition.

(b) Assemble a priority list of USAF runways requiring corrective measures to prevent skidding and hydroplaning accidents.

(c) Determine optimum runway surfaces.

(d) Investigate a water-depth warning system or other measuring system.

The preliminary results of Project Combat Traction have been reported in references 17 and 18 and the final results are presented in this paper.

Appendix A presents a compilation of the test data. Methods used to compute the data are presented in appendix B. Civil engineering descriptions of the runways tested, if available, are presented in appendix C. Appendix D presents the results of tests conducted by the British Ministry of Aviation Supply.

SYMBOLS

The data are referred to the body-axis system except the lift and drag coefficients which are referred to the stability-axis system. The estimated center-of-gravity location for the C14A aircraft tests was at $0.28\bar{c}$. All coefficients are based on the projected wing planform area and mean geometric chord. Pitching-moment coefficient $C_{m,g}$ was determined about the intersection of the main-gear strut center line and the ground.

a_x uncorrected longitudinal acceleration, ft/sec^2

$\bar{a}_x$ longitudinal acceleration corrected for accelerometer platform attitude, ft/sec^2

C_D three-point aerodynamic drag coefficient for test configuration (take-off flaps, spoilers deployed), $\frac{Drag}{qS}$

C_L three-point aerodynamic lift coefficient for test configuration (take-off flaps, spoilers deployed), $\frac{Lift}{qS}$

$C_{m,g}$ pitching-moment coefficient about intersection of main-gear strut center line and ground, $\frac{Moment}{qS\bar{c}}$

$\bar{c}$ mean geometric wing chord, 266.5 inches

D uncorrected stopping distance, ft

D_{corr} corrected stopping distance from a brake engagement ground speed of 100 knots to a full stop, ft

ΔD_B incremental distance from brake engagement to $V_G = 100$ knots (positive when $V_{G,B} < 100$ knots; negative when $V_{G,B} > 100$ knots), ft

ΔD_{final} incremental distance from brake release to a full stop (positive always since $V_{G,final} > 0$)

$F_{z,m}$ vertical load on main gear (instantaneous computation during a braking run), lb

g acceleration due to gravity, 32.17 ft/sec^2

h_{cg} vertical displacement of center of gravity from ground, ≈96.0 inches

$K_{a,x}$ accelerometer sensitivity constant, counts/ft/sec^2

p_a ambient pressure during braking test, lb/ft^2

q free-stream dynamic pressure, lb/ft^2

S projected wing planform area, ft^2

$S, S_1, S_2, \ldots S_6$ runway distances (fig. 25)

T_a ambient temperature, ^{o}Rankine

T_n installed idle thrust (from engine manufacturer's data), lb

t time measured from V_{Go}, sec

Δt time increment

V_A airspeed, ft/sec

V_G ground speed, ft/sec

V_w wind velocity component parallel to runway center line (positive, when headwind; negative, when tailwind), ft/sec

ΔV velocity increment

W configuration test weight (estimated from empty weight + crew + cargo + fuel for each test run), lb

$\overline{X}, X_A, X_B, X_C$ stopping distance ratios (fig. 25)

Δx longitudinal distance between nose and main gears, 636.0 inches

Δx_g longitudinal distance from center-of-gravity station to main gear, ≈48.75 inches

y vertical axis

α angle of attack, deg

ϵ thrust misalinement angle, 0^{o}

μ_B braking friction coefficient

μ_R rolling friction coefficient, 0.015 (assumed)

μ_{wet}, μ_{dry} wet and dry braking friction coefficients, respectively

Subscripts:

o	initial condition
B	condition at brake engagement
Braked	condition measured during maximum braking
final	condition at braked release
R	condition measured during free-rolling tare test
RDG	raw test data
Zero	data zero

ABBREVIATIONS

AC	asphaltic concrete
ALPA	Air Line Pilots Association
ASTM	American Society For Testing Materials
ATA	Air Transport Association
BS	British standard
CBR	California bearing ratio
CL	clay
DBT	double bituminous surface treatment
FAA	Federal Aviation Administration
Grade 200 pen	Penetration petroleum bitumen

K	number indicates subgrade reaction
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
PCC	Portland cement concrete
PSP	pierced steel planking
RAE	Royal Aircraft Establishment
RAF	Royal Air Force
RAFB	Royal Air Force Base
RCR	runway condition reading
RN	Royal Navy
R/W	runway
S.O.	Specification officer
USAF	United States Air Force

TEST APPARATUS

Test Vehicles

Aircraft.- A C-141A aircraft (fig. 1(a)) was chosen as the test aircraft for a number of reasons: (1) the four-wheel main-gear bogies of this aircraft provide maximum safety for the kind of testing contemplated; (2) thrust and drag can be determined; (3) the braking and antiskid systems are well suited to the project; and (4) its range and cargo capacity would solve a formidable logistics problem concerning the moving of a 20-man test crew, the test equipment, and a test vehicle from one location to another, in the United States and in Europe, within a short period of time. The test crew included the project pilot, the copilot, two flight engineers, a navigator, a four-man maintenance crew, the project manager, the flight test engineer, a civil engineer from the U.S. Air Force, and a seven-man NASA crew. Test equipment carried onboard the aircraft included data



(a) C-141A test aircraft.



(b) NASA test vehicle.



(c) RCR vehicle. L-70-4790

Figure 1.- Test apparatus.

recorders, spare tires for the aircraft and test vehicle, camera equipment, aircraft jacks, runway markers, and film.

Ground vehicles.- Since the 1968 NASA studies at Wallops Station (ref. 1) had clearly demonstrated that wet-dry stopping distance ratios obtained by the diagonal braking technique correlated better with test aircraft wet-dry stopping distance ratios, a 1969 sedan (see fig. 1(b)) was equipped with a diagonal-braking system. The diagonal-braking system was obtained by installing cutoff valves in the brake lines. (See fig. 2.) Thus, by appropriate valve selections, one pair of diagonal wheels on the automobile could be braked while the opposite pair of wheels remained unbraked and freely rolling. They were then free to steer or develop cornering or side forces for maintaining vehicle stability. The diagonal-braked wheels were equipped with the ASTM bald-tread tires (Specification E249) and the unbraked wheels were equipped with conventional rib-tread tires. The use of bald tires on the braked wheels essentially eliminates the effects of tire-tread design on braking traction; hence, repeatable data could be obtained. This diagonal-braking technique makes it possible for the test vehicle to enter locked-wheel skids at high speeds on wet pavements, and even on snow- and ice-covered pavements and still maintain good directional control.

Provisions were made in the diagonal-braked test vehicle instrumentation for the measurement and recording of ground-speed, stopping distance, angular velocity on individual wheels, longitudinal acceleration, and brake pressure.

The Air Force runway condition reading (RCR) vehicle from the local base was utilized in the tests at USAF bases since it represented the system currently employed worldwide by the U.S. Air Force to predict operational stopping distances for aircraft in adverse weather. Each test site provided an RCR vehicle such as the one shown in figure 1(c).

The Mu-meter and Miles engineering skid trailer were tested concurrently with the C-141A and diagonal-braked vehicle at the British Royal Air Force (RAF) and Royal Navy (RN) Bases.

Instrumentation

Aircraft.- Four recorders were used to record the following information with respect to time on $6\frac{1}{2}$-inch-wide photographic film:

Recorder 1 recorded the following:

(a) Event marker, actuated by the flight test engineer, to indicate entry into the test section and passage of each runway marker.

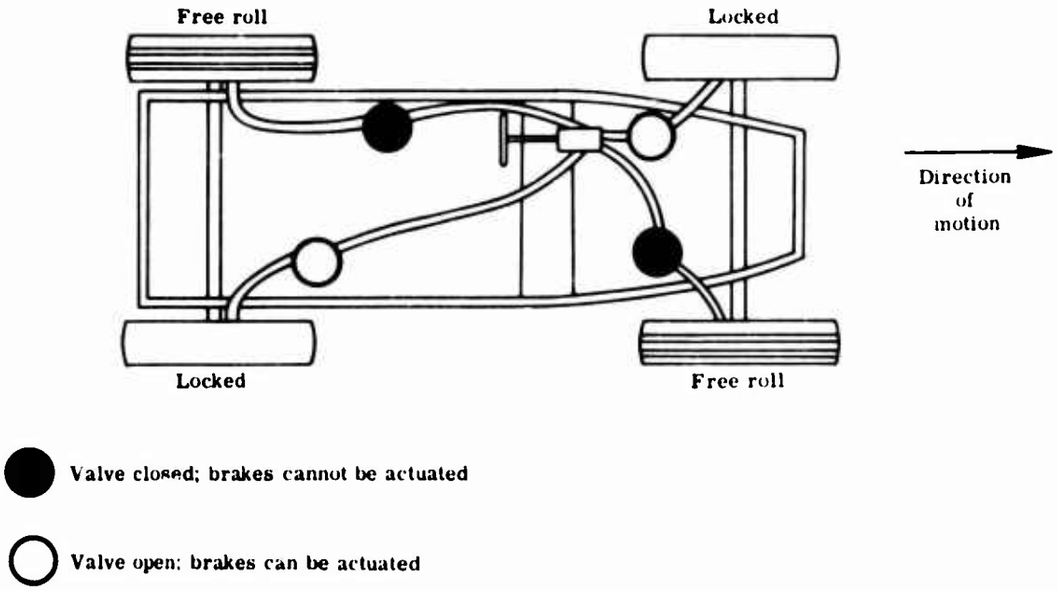


Figure 2.- Braking system for NASA diagonal-braked test vehicle.

(b) Angular velocity of the nose wheel as sensed by a magnetic pickup and a 90-tooth steel ring mounted on the left nose wheel. The output from the magnetic pickup was converted to a direct current voltage proportional to the input frequency; this voltage was recorded on the oscillograph and displayed to the pilot on an instrument calibrated in ground speed.

(c) Angular velocity of each main wheel. The signal from the frequency generator of the antiskid system was converted to a dc voltage proportional to the input frequency and fed to the oscillograph.

(d) Position of the antiskid modulating valve for each main wheel was obtained by recording the dc voltage input to the valve solenoid.

Recorder 2 obtained:

(a) Actuation of the event marker, as for recorder 1.

(b) Longitudinal, lateral, and normal accelerations, as measured by three accelerometers having a range of +1g to -1g, +1/2g to -1/2g, and 0 to 2g, respectively, and a dc output of 0 to 5 volts. The accelerometers were mounted on a single bracket near the center of gravity on the lower side of the wing carrythrough structure at 0.36$\bar{c}$.

(c) Pitch and yaw attitudes (used to correct longitudinal acceleration) were measured by a pitch-yaw attitude gyro with direct-current signals transmitted from a potentiometer.

(d) Nose-wheel steering angle, as measured by a direct current voltage from a potentiometer.

(e) Elevator position, as measured by a potentiometer mounted underneath the cockpit and attached to the elevator control cable. The dc signal was generated by a potentiometer.

(f) Main landing-gear and nose landing-gear strut pressures, which indicated vertical load on the tires. These values were used to calculate coefficient of friction and were measured by a 0 to 3000 psi pressure transducer with a 0 to 5 volt output. The strut filler valve was removed and replaced by a tee; the filler valve was placed in one side of the tee and the transducer in the other side.

(g) A reference for the pitch, yaw, and the accelerometer traces, provided by a vertical gyro.

Recorder 3 recorded:

(a) Event marker actuation, as for recorders 1 and 2.

(b) Pressure of each of the eight brakes, as sensed by a 0 to 3000 psi transducer, which provided a 0 to 5 volt dc output.

(c) An indication of left and right brake system pressures as provided by 0 to 3000 psi transducers, with an output of 0 to 2 volts dc, placed upstream from the modulating valves, to indicate when sufficient brake pressure was available to operate the antiskid system.

(d) The antiskid dump valve position for each main wheel, as indicated by the dc voltage input to the valve solenoid.

Recorder 4, an FM tape recorder, was used to record each actuation of the event marker and the vibration input to the fuselage from the landing gear on some of the runs. The information was provided by two accelerometers with a range of $\pm 2\frac{1}{2}$g mounted high on the strut (near the fuselage) to measure vertical and longitudinal vibrations.

Stopping distance was determined by mounting a brake-actuated switch, a magnetic pickup, and a single-tooth ring mounted on the left nose wheel to count the number of wheel revolutions from brake application to brake release. The data were displayed by an electronic counter and recorded by the flight test engineer.

Ground vehicles.- On the diagonal-braked test vehicle a ten-channel recorder was used to record the following information with respect to time:

(a) Event marker, a pressure switch in the brake system actuated the event marker when the brake was applied, and a timer reactuated it at 1-second intervals as long as braking was applied.

(b) Longitudinal acceleration, as measured by an accelerometer with a range of 0 to 1g.

(c) The angular velocity of each vehicle wheel, as measured by a generator.

(d) Angular velocity of a trailing fifth wheel, as measured by a generator.

(e) Hydraulic pressures, as measured with pressure transducers on the left front brake and right rear brake.

(f) Stopping distance as measured by a mechanical and an electronic wheel revolution counter mounted on a trailing fifth wheel and actuated by a brake pressure switch.

The RCR vehicle instrumentation consisted of a James brake decelerometer mounted on the front floor of an operations vehicle. (See ref. 19.) The data were recorded by the vehicle operator.

Other Instrumentation

Water depth.- Water depth was measured by a gage (ref. 20) designed by NASA for this program. (See fig. 3.) The gage works on the principle of reflectivity. Plexiglass rods of different lengths that protrude through its body are marked with numbers from



L-69-6167

Figure 3.- NASA water depth gage.

0.010 to 0.100 inch to indicate water depth. Since water is highly reflective and will reflect more light than the runway surface, rods that are not touching the water will appear lighter than those that are touching or submerged in water. The dark rod with the highest number, therefore, indicates the water depth. In figure 3, for example, the gage indicates a water depth of 0.020 inch.

Texture depth.- A runway texture-depth measuring kit (fig. 4), developed by NASA (ref. 21), was used to measure the depth of the surface texture of most of the runways. For this measurement, 1/2 cubic inch of grease was spread on the runway with a rubber squeegee in an area between two strips of masking tape laid 4 inches apart.

When the grease was evenly spread, the area covered was measured. The volume of grease (1/2 cubic inch) was divided by the area covered and the result indicated the average texture depth of the surface.

Photographic coverage.- A vibration-free camera mount was installed in a helicopter for photographic coverage during the wet tests. A motion-picture camera with a 12- to 120-millimeter zoom lens and photographing 24 frames per second was installed on the mount to take overhead color motion pictures of the aircraft landings and brake runs and the brake runs of the diagonal-braked and RCR test vehicles. The helicopter usually flew at an altitude of about 1000 feet so that two runway markers would appear in each picture frame; in case the aircraft instrumentation malfunctioned, this technique would provide enough data to calculate the aircraft velocity when entering the test section and the deceleration and stopping distances. A cameraman on the ground also took color motion pictures of each aircraft and vehicle test run. Only the ground photographic coverage was provided for the ice and snow tests.

The tests at Wallops Station were covered by six 16-millimeter color motion-picture cameras and one television camera. Two hydraulically operated (with azimuth and elevation control) gun mounts were converted to camera mounts and placed about 800 feet from each side of the runway. Each camera mount held two cameras: one, using a 4-inch lens and taking 128 frames per second, was focused on the aircraft; the other, using a 10-inch lens and taking 200 frames per second, was focused on the wheels. The wheels were painted with four white radial stripes to indicate wheel rotation or skid. These cameras tracked the aircraft from just prior to touchdown to test-section exit. A remotely operated end-of-the-runway camera, with a 10-inch lens and taking 48 frames per second, recorded all directional control problems encountered during each test run. The helicopter-mounted color camera was supplemented by a television camera held by the same mount. These cameras provided overhead coverage to record aircraft directional stability and water-spray patterns. The television transmissions were recorded to provide a quick review of the test runs by the ground and flight test crew.



L-70-4791

Figure 4.- Runway texture depth measuring kit.

Runway markers.- Three lead-in markers and seven test-section markers were located along the right-hand side of the runway at 500-foot intervals as shown in figure 5. The first lead-in marker was located 1500 feet from the beginning of test section toward the approach end of the runway. These markers were used to guide the pilot in entering the test section at the proper speed. The test-section markers, lettered A to G, served as reference points to the flight test engineer for actuating the event marker on the airborne recorder and to the ground crew for locating where the brakes were applied and released.

Atmospheric data.- Wind direction and velocity was provided by the airfield control tower and by a hand-held anemometer. Temperature and barometric pressure measurements were also provided by the control tower.

TEST PROCEDURES

Wet and Dry Runways

For the wet and dry runway tests, the aircraft and crew landed at the test base in the afternoon preceding the day of the test. In addition to a printed briefing mailed several weeks prior to the scheduled arrival time, a verbal briefing was held on the afternoon preceding the test for the benefit of the base personnel required to take part in the test and to select the runway test section. Each base furnished water for wetting the runway, a water coordinator, transient aircraft maintenance, operations vehicle driver, a ground cameraman, base photographic facilities, and a helicopter for aerial photographic coverage.

The target start time was 1/2 hour before daylight with a short check-in meeting at Base Operations, where a weather decision was made and portable radios and water-depth gages were issued to the test personnel. The runway crew was dispatched to the runway to lay out the selected test section with portable runway markers.

After the runway markers were in place, the aircraft and helicopter took off. The aircraft made three landings, the first of which was a touch-and-go landing so that the pilot could verify the approach and landing speed required to enter the test section under the proper conditions (100 knots ground speed as measured by the segmented ring on the nose wheel, flaps in take-off position, spoilers up, and engines at idle thrust).

The second landing was a maximum-braking stop on the dry runway. The pilot applied maximum braking as he passed the A marker and held full brakes until the aircraft had slowed to approximately 10 knots. The flight test engineer who occupied the jump seat actuated the event marker as the aircraft cockpit passed each runway marker. An observer stationed beside the runway near the A marker marked with paint the location where the over-the-wing light came on and indicated brake application. Similarly,



L-69-294

Figure 5.- Runway markers.

another observer near the aircraft expected stopping point marked the location where the over-the-wing light was extinguished and indicated brake release. Stopping distance was then determined by measuring the distance between the first and second marks. Since brake release occurred at a speed of approximately 10 knots, an extrapolation of distance from the velocity recording history was used to determine the remaining distance that would have been required to come to a complete stop. Full braking was not normally used below 10 knots because the antiskid system disarmed and the wheels would lock up and cause excessive tire damage. The stop was followed by a tire and brake inspection by the maintenance crew.

Before the third landing, the aircraft took off to air-cool the brakes. While the brakes were being air-cooled, the water trucks were placed on the runway and the artificial wetting operation was initiated. To provide the necessary wetting without excessive water loss by drainage and evaporation, it was necessary to place approximately 9000 gallons of water on a 40- by 1500- to 2500-foot runway strip within 8 minutes and have the aircraft land within 2 minutes after completion. The pilot was continually advised by tower personnel of the wetting progress so the aircraft could be positioned to land within the prescribed time. The third landing was then made on the wet runway using the technique described for the maximum-braking dry stop. The aircraft then promptly cleared the runway, after which the NASA diagonal-braked test vehicle and the RCR test vehicle made their runs. The elapsed time between aircraft test-section entry and completion of the vehicle runs was never more than 3 minutes and usually less than 2 minutes.

The diagonal-braked test vehicle began each run at 60 miles per hour. The left-front and right-rear wheels were locked with brakes, and the brakes kept fully on until the vehicle came to a complete stop. Stopping distance was measured by the trailing fifth wheel and recorded by the driver. These runs were made slightly outboard of the tracks left by the right main gear. Since the test vehicle stopping distance was about one-third that of the aircraft, the test vehicle, attempting to cover the entire length of stopping path traversed by the aircraft, made as many runs as time permitted. The test vehicle stopping distances were then averaged. At the same time, the RCR test vehicle took a similar series of readings just outboard of the track of the left main gear. Each reading was made in accordance with the technique described in reference 19. RCR readings on the dry runway were taken on the test section just after the aircraft had made its maximum-braking dry stop. Since skidding to a stop on two locked wheels on a dry surface from 60 miles per hour usually rendered the tires unfit for further use, the dry stopping distance of the diagonal-braked test vehicle was determined after all wet runs had been completed by using an adjacent section of runway which had not been wetted. The braked tires were then changed in preparation for the next day's testing. In the tests conducted on British airfields, the Mu-meter and the Miles engineering skid trailer were tested concurrently

with the RCR and diagonal-braked test vehicles. The entire test operation required about 1 hour and 45 minutes to complete.

Snow-, Slush-, and Ice-Covered Runways

Unlike the summer program, where the tests were scheduled several months in advance, the usual procedure for the ice and snow test was to locate an airfield with snow or ice on the runway within 1 or 2 hours flying time of the last runway measured. The base operations officer was then contacted by telephone for permission to test the runway on a noninterference basis; however, because of the efficiency of the snow removal crews, it was usually difficult to find a runway completely covered with ice or snow.

After selecting a snow-covered airfield, the aircraft and test crew would arrive at the site and present a short briefing to the base operations officer covering test procedures and assistance needed. The runway was then surveyed by the diagonal-braked and RCR vehicles before the aircraft was committed to a test. The narrow tread of the C-141A landing gear permitted testing on both sides and the center of the runway. (The usual procedure followed by the snow removal crews was to clear the center portion of the runway first, and to leave the sides covered with snow and ice.) After the survey by the diagonal-braked test vehicle, the aircraft usually made several runs on different sections of the runway to take advantage of the various conditions. Taxiways were also tested by the vehicles and aircraft when the proper conditions were present. The diagonal-braked test vehicle and RCR test vehicle made runs both before and after the aircraft and each test vehicle's readings were averaged. Because the runway surface was covered with ice or snow, dry runs could not be made by the vehicles or the aircraft. Therefore, an average dry stopping distance of 1100 feet was used for the aircraft and 302 feet for the diagonal-braked test vehicle.

NASA Landing Research Runway

The landing research runway at NASA Wallops Station is described in appendix C. The procedure for tests at this facility is described in detail in reference 1.

RESULTS AND DISCUSSION

The present investigation of aircraft and ground vehicle braking performance on runways included full-stop braking tests on active runways in the United States and Europe under dry, wet, slush, snow, and ice conditions; and limited braking tests on short (approximately 350 feet) test surfaces of the research runway at NASA Wallops Station under dry, wet, flooded, and slush-covered runway conditions. The results of these tests and a discussion of the correlation of the techniques are included in the following sections along with an evaluation of the relative slipperiness of surfaces.

Full-Stop Runway Braking Tests

The corrected stopping distances required to brake the C-141A aircraft to a stop from 100 knots ground speed, and the NASA diagonal-braked test vehicle from a speed of 60 miles per hour to a stop are presented in appendix A for each runway tested. It should be noted that two independent methods were used to determine the aircraft stopping distance. In one method, the stopping distance was obtained directly from the nose-wheel revolution counter installed on the C-141A aircraft (and described in the instrumentation section of this paper). In the other method, the stopping distance was obtained from an integration of the aircraft deceleration time history measured during a braking run. Also shown in each figure are the calculated effective tire-ground friction coefficients developed by the aircraft during the braking runs. The computer program required to obtain the aircraft stopping distance and effective friction coefficients from acceleration measurements is described in appendix B.

Also tabulated in the figures of appendix A are the pavement, atmospheric, and aircraft test conditions, along with measured values of RCR and average texture depth of the pavement. A photograph of the runway surface in the area tested by the aircraft and the diagonal-braked test vehicle is also shown. For each figure and runway are presented the results of the core sample analysis, where available. These analyses were made by the USAF Weapons Laboratory for U.S. Air Force runways and by the Ministry of Public Buildings and Works for British runways. Civil engineering descriptions of each runway surface tested under dry and wet conditions are listed in appendix C. Each runway tested is assigned a runway reference number based on its slipperiness determined by tests as shown in table I. Concrete runways are listed separately from asphalt runways. Thus, runway numbers 1 to 16 refer to the concrete runways and numbers 17 to 39 refer to the asphalt runways. Runway 40 is a landing mat surface.

Full-stop aircraft and test vehicle braking tests were also carried out on nine runways and taxiways where the pavement surface was coated with snow, slush, or ice. These runways are assigned runway numbers 41 to 49 as shown in table II.

Dry-runway braking characteristics.- For most of the dry runways, the antiskid system of the C-141A tended to develop maximum braking efficiency at the higher ground speeds. A much lower braking efficiency usually developed at the lower ground speeds because of less effective wheel skid control which resulted in excessive cycling and dumping of wheel brake pressure. This antiskid operational feature on dry runways usually resulted in a decrease in the effective tire-ground friction coefficients generated by the aircraft braking system with decreasing ground speed. (See fig. A1.) This trend is not attributed to brake fade during an aircraft stop since the wheels are not torque limited at low speeds. The test records show that the main gear wheels develop deep skids and frequent wheel lockups at the lower ground speeds as shown in figure 6(a).

TABLE I.- SUMMARY OF DATA OBTAINED ON WET RUNWAYS

Runway	Airport	Material	Surface treatment	Test condition	Average antiskid stopping distance ratio		
					Aircraft*	Test vehicle	
1	Dyess AFB	Concrete	Conventional	Artificially wet	2.27	2.74	1.28
2	England AFB	Concrete	Conventional	Artificially wet	2.47	2.19	1.47
3	Marham RAFB	Concrete	Conventional	Artificially wet	2.24	1.92	1.06
4	Offutt AFB	Concrete	Conventional	Artificially wet	2.21	2.15	1.24
5	Ellington AFB	Concrete	Conventional	Light rain	2.17	2.19	2.00
6	Edwards AFB	Concrete	Conventional	Artificially wet	2.15	1.91	1.19
7	Wright-Patterson AFB	Concrete	Conventional	Artificially wet	2.12	1.95	1.04
8	Lockbourne AFB	Concrete	Conventional	Artificially wet	2.05	1.84	1.02
9	Langley AFB	Concrete	Conventional	Artificially wet	1.90	1.95	1.41
9	Langley AFB	Concrete	Conventional	Damp after light rain	1.42	---	---
10	Yeovilton RNB	Concrete	Wire combed	Artificially wet	1.78	1.65	.96
11	Yeovilton RNB	Concrete	Scored transversely	Artificially wet	1.65	1.76	1.15
12	John F. Kennedy Airport	Concrete	Grooved, $1\frac{3}{8}$ in. by 3/8 in. by 1/8 in.	Artificially wet (clean)	1.57	1.75	---
12	John F. Kennedy Airport	Concrete	Grooved, $1\frac{3}{8}$ in. by 3/8 in. by 1/8 in.	Artificially wet (rubber deposits)	1.86	2.20	---
13	Seymour Johnson AFB	Concrete	Grooved, 2 in. by 1/4 in. by 1/4 in.	Artificially wet (clean)	1.38	1.35	1.21
13	Seymour Johnson AFB	Concrete	Grooved, 2 in. by 1/4 in. by 1/4 in.	Artificially wet (rubber deposits)	1.47	1.50	1.21
14	Chicago Midway Airport	Concrete	Grooved, $1\frac{1}{4}$ in. by 1/4 in. by 1/4 in.	Artificially wet	1.25	1.35	---
15	Offutt AFB	Concrete	Grooved, $1\frac{1}{4}$ in. by 1/4 in. by 1/4 in.	Artificially wet	1.20	1.32	1.24
16	Beale AFB	Concrete	Grooved, 1 in. by 1/4 in. by 1/4 in.	Artificially wet	1.11	1.20	1.05
17	Mildenhall USAFE**	Asphalt	Slurry seal	Artificially wet	---	3.15	---
18	Spangdahlem USAFE	Asphalt	1/8 in. German antiskid coat	Artificially wet	2.35	2.50	1.41
19	Elmendorf AFB	Asphalt	Plant mix	Artificially wet	2.32	2.48	1.53

*Average value of revolution-counter and acceleration-time measurements.

**Resurfaced with porous friction course, November 1970.

TABLE I.- SUMMARY OF DATA OBTAINED ON WET RUNWAYS – Concluded

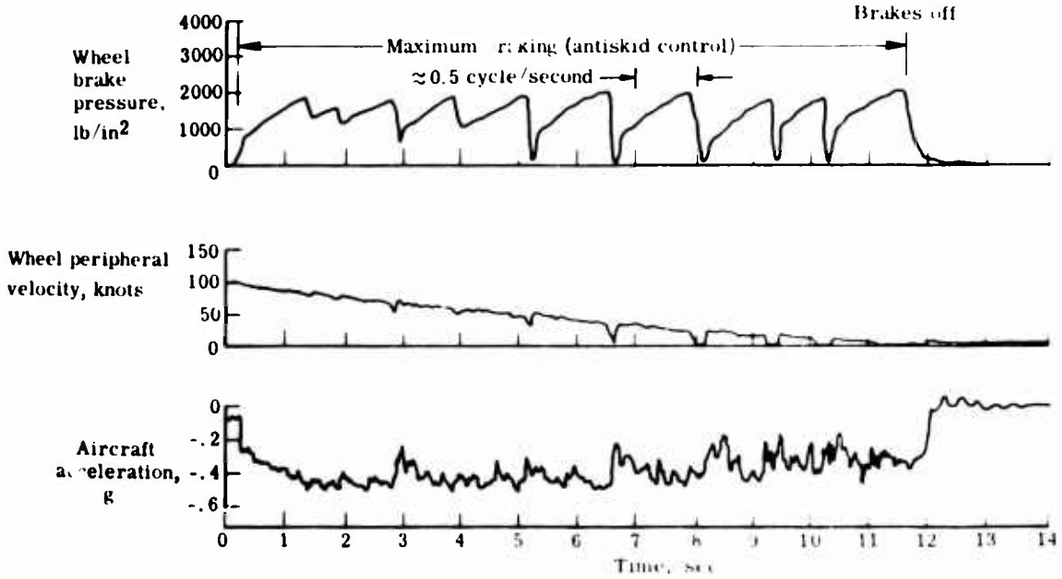
Runway	Airport	Material	Surface treatment	Test condition	Average wet-dry stopping distance ratio		RCR dry-wet ratio
					Aircraft (*)	Test vehicle	
20	Bitburg USAFE	Asphalt	Marshall asphalt	Artificially wet	1.97	1.78	1.09
21	Myrtle Beach AFB	Asphalt	Slurry seal	Damp after light rain	1.08	---	1.05
21	Myrtle Beach AFB	Asphalt	Slurry seal	Artificially wet	1.92	1.67	1.02
22	Waddington RAFB	Asphalt	1/8 in. surface dressing	Artificially wet	1.82	1.87	---
23	Otis AFB	Asphalt	Plant mix	Artificially wet	1.81	1.62	1.18
24	Aviano USAFE	Asphalt	Crushed rock seal coat	Artificially wet	1.76	1.57	1.10
25	Alconbury USAFE	Asphalt	Slurry seal	Artificially wet	1.71	1.68	1.10
26	Farnborough RAE	Asphalt	Plant mix – grooved 1 in. by 1/8 in. by 1/8 in.	Artificially wet	1.69	1.40	1.05
27	Sembach USAFE	Asphalt	1/8 in. German antiskid coat	Artificially wet	1.67	1.50	1.13
28	Pope AFB	Asphalt	Plant mix	Artificially wet	1.56	1.78	1.19
29	Tempelhof Airport	Asphalt	1/8 in. German antiskid coat – grooved $1\frac{1}{2}$ in. by 3/8 in. by 3/8 in.	Artificially wet	1.51	1.65	1.41
30	McChord AFB	Asphalt	Plant mix	Moderate rain	1.49	1.94	---
31	Little Rock AFB	Asphalt	Plant mix	Artificially wet	1.48	1.61	.96
32	Scott AFB	Asphalt	Plant mix	Artificially wet	1.40	1.80	1.16
33	Dover AFB	Asphalt	Plant mix	Artificially wet	1.33	1.50	1.18
34	Nellis AFB	Asphalt	Plant mix	Artificially wet	1.32	1.60	1.02
35	NASA Wallops Station	Asphalt	Slurry seal	Artificially wet	1.28	1.29	1.05
36	Farnborough RAE	Asphalt	$1\frac{1}{4}$ in. porous friction course	Artificially wet	1.18	1.05	.87
37	Shemya AFB	Asphalt	Plant mix	Artificially wet	1.15	1.45	1.07
38	Marham RAFB	Asphalt	3/4 in. porous friction course	Artificially wet	1.12	1.10	1.00
39	Meigs Airport	Asphalt	Plant mix – synthetic aggregate	Artificially wet	---	1.17	---
40	Dyess AFB	Landing mats	Epoxy-grit coated aluminum	Artificially wet	2.05	1.66	1.02

*Average value of revolution-counter and acceleration-time measurements.

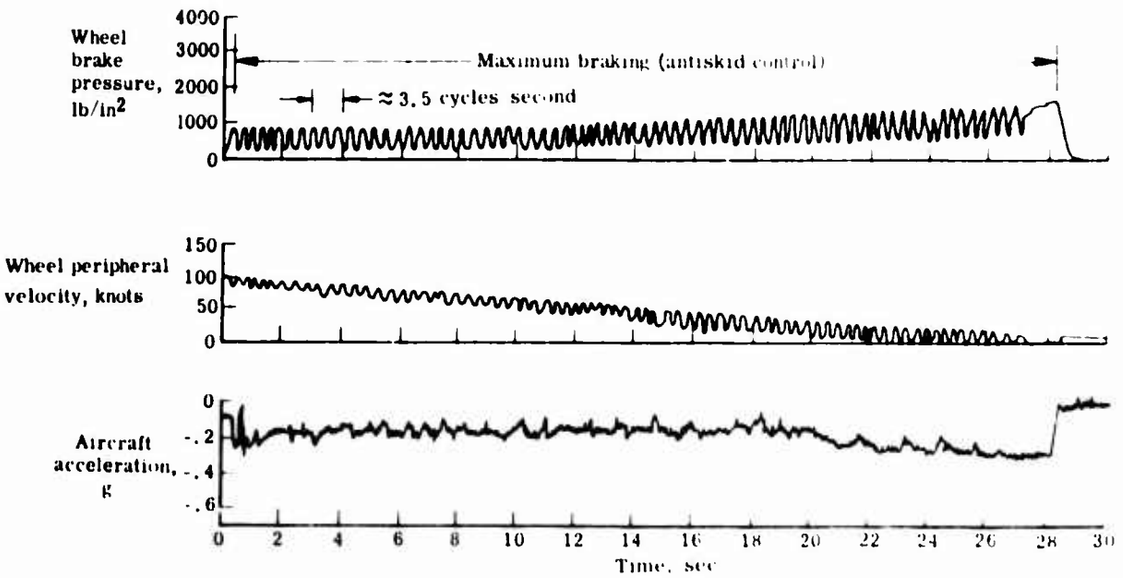
TABLE II.- SUMMARY OF DATA OBTAINED ON SNOW, SLUSH, AND ICE-COVERED RUNWAYS

Runway	Airport	Material	Surface treatment	Test condition		Average wet-dry stopping distance ratio		RCR dry-wet ratio
				Temperature, °F	Surface cover	Aircraft (*)	Test vehicle	
41	Malmstrom AFB	Concrete (ramp)	Conventional	27	Packed dry snow	3.71	4.16	6.00
42	Loring AFB	Asphalt	Slurry seal	21	Glazed ice and dry snow	3.51	3.40	4.00
43	Wurtsmith AFB	Concrete	Conventional	23	Packed snow and ice	3.31	3.65	12.00
44	Grissom AFB	Asphalt (taxiway)	Plant mix	22	Packed snow and ice	3.20	3.95	4.80
45	Wright-Patterson AFB	Concrete	Conventional	8	Dry packed snow and ice	2.82	2.90	4.36
46	Glenview NAS	Concrete and asphalt	Conventional	27	Patchy ice and snow	2.39	2.51	----
47	K. I. Sawyer AFB	Asphalt	Slurry seal	11	Patchy packed snow and ice	2.27	1.63	----
47	K. I. Sawyer AFB	Asphalt	Slurry seal	23	Packed snow and ice	2.25	2.27	3.20
48	McGuire AFB	Asphalt	Plant mix	14	Patchy snow and ice	1.84	2.17	2.53
49	Malmstrom AFB	Asphalt (runway)	Plant mix	33	Patchy slush	1.75	1.62	1.72

*Average value of revolution-counter and acceleration-time measurements.

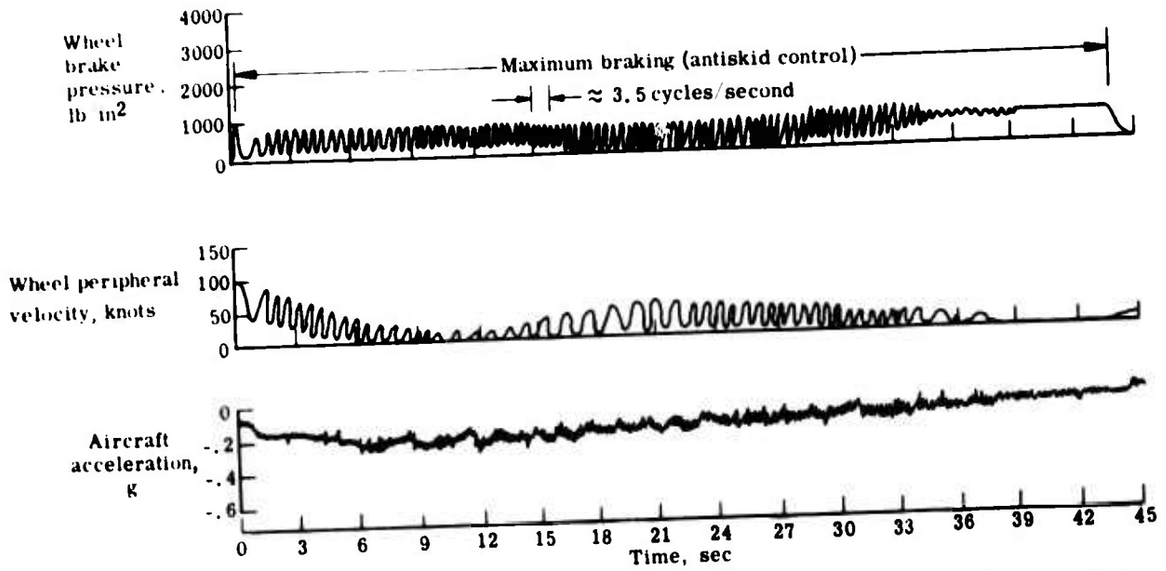


(a) Dry runway condition. Porous friction course at Marham RAFB.



(b) Wet runway condition (low friction). Concrete runway at England AFB.

Figure 6.- Examples of variation in C-141A aircraft wheel brake pressure and velocity and aircraft acceleration during maximum braking conditions on dry, wet, and ice-covered runway surfaces (left rear inboard wheel).



(c) Glazed-ice and snow-covered runway condition. Slurry seal runway at Loring AFB.

Figure 6.- Concluded.

The stopping distances obtained by the C-141A aircraft during braking runs on dry surfaces are given in appendix A. These data produced the average dry stopping distances from 100 knots ground speed as shown in the following table:

Runway surface	Stopping distance, feet		
	Revolution counter	Acceleration time	Average
Asphalt	*1097	1142	1120
Concrete	1022	1092	1058

*Waddington RAFB omitted (Revolution counter reading believed to be in error).

Both the revolution counter and acceleration-time methods of determining aircraft stopping distance indicate that the aircraft requires slightly less distance to stop on dry concrete than on dry asphalt runways. The average of the two methods indicates that the aircraft stopping distance was 1120 feet on asphalt and 1058 feet on concrete, a difference of 62 feet. No distinctive trend could be found for aircraft stopping distance on dry runways with changes in either ambient air temperature (see fig. 7) or aircraft gross weight. It is apparent that deviations in stopping distance on dry runways must occur from differences, as yet undetermined, in antiskid efficiency, wheel brake wear, and effects of pavement surface condition and contamination such as dust, oil films, rubber deposits, and so forth. It should also be mentioned that the aircraft tires were installed on the aircraft in an unused condition; however, some tires were new whereas others were re-caps. The tires were replaced when 50 percent worn. Tire construction effects and different rubber compounding used on the tires tested could also contribute to the deviations in stopping distance encountered. As noted in appendix B, runway slope information provided for the different runways was insufficient to allow slope corrections to be made to the raw data and this fact could also account for some small part of the aircraft stopping distance variations.

The braking system utilized on the NASA diagonal-braked test vehicle caused the diagonal pair of ASTM smooth tread tires to be locked upon brake application by the driver. Thus, the kinetic energy developed by the test vehicle at 60-miles-per-hour brake-application speed on a dry runway was absorbed in a small contact patch on each of the two smooth tread tires. A typical time history of a dry runway braking stop by the diagonal-braked test vehicle is shown in figure 8(a). It can be seen that the deceleration of the test vehicle decreases with time from the initial high value at brake application speed until at some lower speed, the deceleration increases and reaches a peak value similar in magnitude to the initial deceleration peak at brake engagement speed. It is

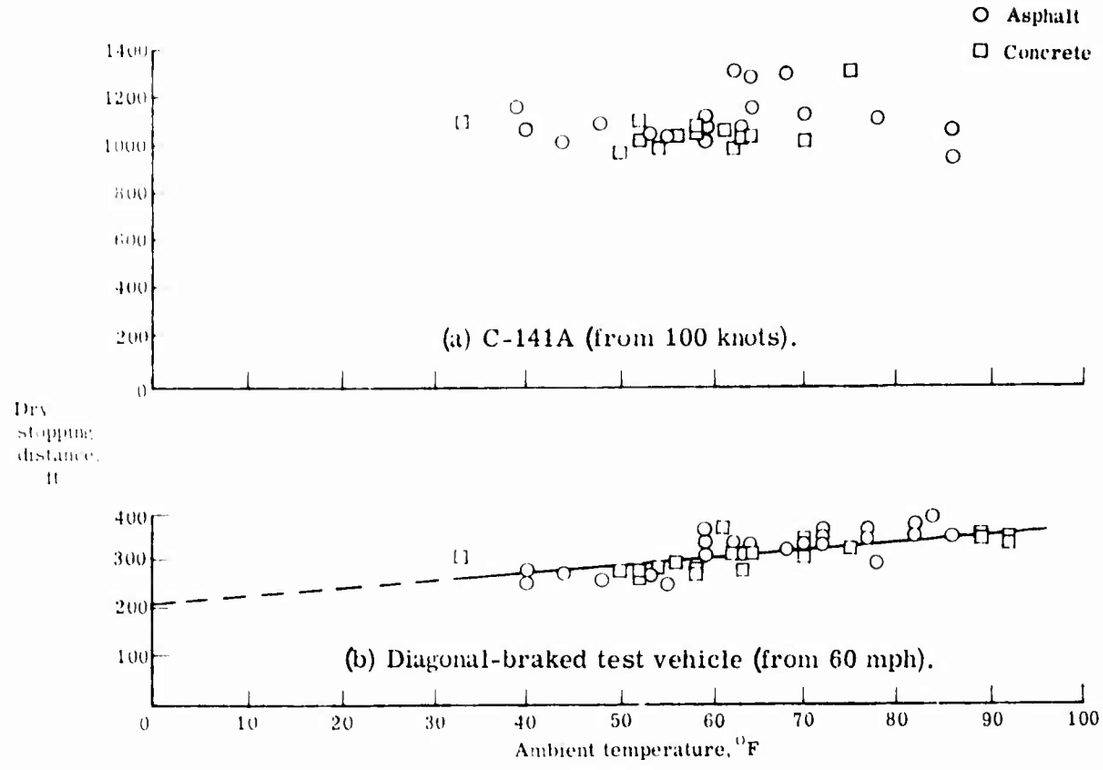
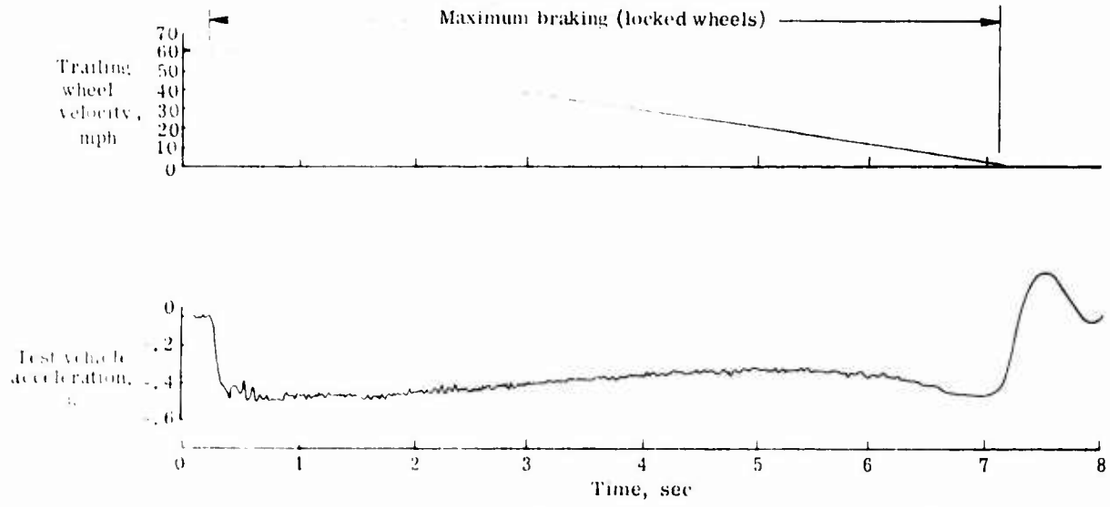
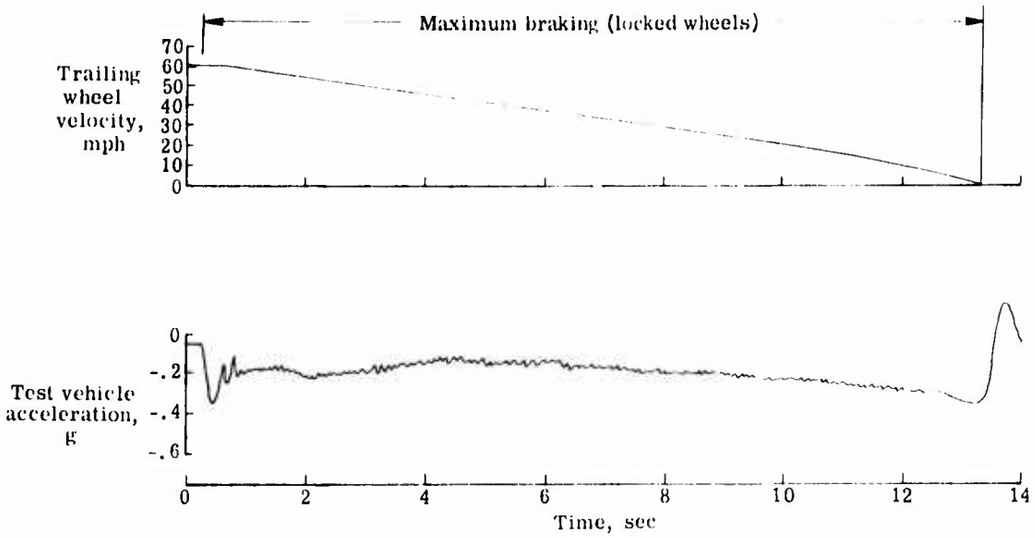


Figure 7.- Effects of runway ambient air temperature on aircraft and test vehicle dry runway stopping distance.

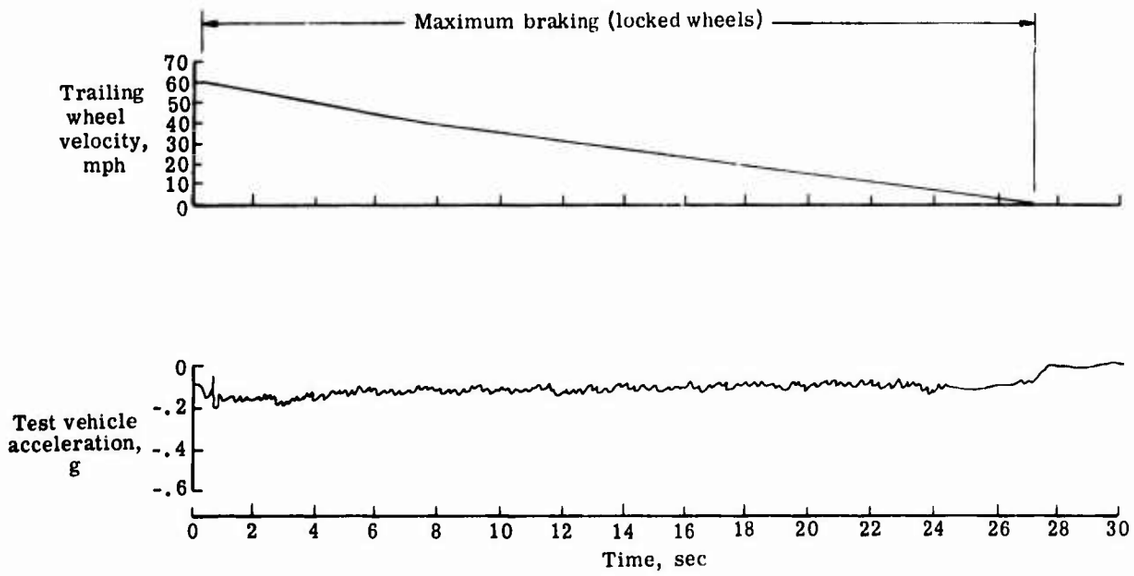


(a) Dry runway condition. Concrete runway at England AFB.

Figure 8.- Examples of variation in diagonal-braked test vehicle velocity and acceleration under locked-wheel braking conditions on dry, wet, and ice-covered runways.



(b) Wet runway condition. Concrete runway at England AFB.



(c) Glazed-ice and snow-covered runway condition. Slurry seal runway at Loring AFB.

Figure 8.- Concluded.

felt that this loss in test vehicle deceleration comes from a loss in tire-ground friction coefficient associated with high rubber temperatures in the skidding tire contact patch.

The locked-wheel operation of the NASA diagonal-braked test vehicle differed from the typical antiskid controlled braking of the C-141A aircraft tires where the rotating tires continuously introduced new rubber into the tire-ground contact area. At low ground speeds, locked-wheel skids sometimes occurred for a fraction of a second. In contrast to the aircraft stopping distance results on dry runways, which showed no effect of runway ambient air temperature, the test vehicle stopping distance on dry surfaces tends to increase with increasing runway ambient air temperature as shown in figure 7. No discernible difference in stopping distance could be detected for the test vehicle between dry asphalt and dry concrete runway surfaces. The variation in diagonal-braked test vehicle stopping distances with air temperature can be approximated by the empirical equation

$$D_{vehicle,dry} = 208 + 1.45T_r \qquad (1)$$

where T_r is the runway ambient air temperature in degrees Fahrenheit, and $D_{vehicle,dry}$ is the stopping distance (from 60 mph) in feet. Equation (1) was derived from the range of runway ambient air temperature (33° F to 92° F) studied in this investigation. It is noted in figure 7 that considerable data scatter exists from the values predicated by equation (1). The aircraft tires used were from several different tire manufacturers, whereas the ASTM tires used on the test vehicle were constructed by one tire company according to rigid and detailed ASTM specifications on tire construction and tread rubber composition. Therefore the data scatter shown for the vehicle dry stopping distance cannot be attributed to the vehicle test tires. It is probable that factors such as measurement accuracy, wind velocity and direction, runway slope, and possibly changes in vehicle rolling resistance contributed to the scatter of the vehicle dry-stopping-distance data.

Wet-runway braking characteristics.- Before attempting to describe the aircraft performance on wet runways, it is first necessary to define runway wetness. Under damp or wet pavement conditions, viscous hydroplaning or skidding is the predominant factor contributing to losses of vehicle tire braking and steering capability. For predominantly viscous hydroplaning conditions, the texture of the pavement and the skid resistance of the exposed aggregate determine the degree of slipperiness of the pavement. Only thin water films (less than 0.01 inch thick) are required for viscous hydroplaning effects to produce drastic tire friction losses on smooth pavements. A damp-runway condition is defined as having a moist (discolored) surface where the average water depth is 0.01 inch or less on the pavement as measured by the NASA water depth gage. (See fig. 3.) A wet-runway condition is defined as having a moist surface where the average water depth lies between 0.01 and 0.1 inch as measured by the NASA water depth gage. When the average

water depths on typical runway surfaces exceed 0.1 inch, additional losses in tire braking and cornering performance occur because of dynamic hydroplaning on worn aircraft tires. New tires with full tread depth require larger average water depths from 0.2 to 0.3 inch for dynamic hydroplaning to occur. A flooded runway is therefore defined as having an average water depth on the pavement greater than 0.1 inch as measured by the NASA water depth gage.

The wet-runway conditions can be simulated by artificial wetting as was done for most of the runways tested in this investigation. The average water depths obtained by artificially wetting runways in the test program were 0.039 inch for ungrooved concrete pavements, 0.035 inch for ungrooved asphalt pavements, damp to 0.01 inch for grooved pavements with the exception of the John F. Kennedy and Farnborough shallow grooved runways which averaged approximately 0.03 inch, and porous asphalt runways which averaged 0.025 inch. It is interesting to note that a light rain produced a damp surface on the Ellington Air Force Base runway, whereas a moderate rain on the McChord Air Force Base asphalt runway produced an average water depth of 0.02 inch. The McChord airport tower rain gage indicated that the rainfall precipitation rate at time of testing was approximately 0.3 inch per hour. From this correlation it is apparent that the artificial wetting technique utilized in this investigation was the equivalent of light to moderate natural rainfalls on the runways with conventional surfaces. The artificial wetting technique was only able to produce a damp condition on deeply grooved runway surfaces.

The braking characteristics of the C-141A aircraft on wet runways can be considerably different than those on dry runways, especially for smooth textured runways where viscous hydroplaning effects predominate. For example, figure 6(b) shows the time history of the aircraft longitudinal deceleration and left rear inboard wheel brake pressure and velocity developed during a braking stop on the wet runway at England Air Force Base (wet-dry stopping distance ratio, 2.47). It can be seen that the antiskid cycling increased from approximately 1/2 cycle per second for the dry runway (fig. 6(a)) to approximately 3.5 cycles per second for the wet runway (fig. 6(b)). As the aircraft speed decreased during the braked roll, the wheel skids became progressively deeper until at approximately 30 knots ground speed, the wheel was cycling under full skid (locked-wheel) conditions.

NASA research reported in reference 18 indicates that aircraft tires encounter a complete loss in cornering or side-force capability when the braked wheels operate at slip ratios greater than 0.25. (See fig. 9.) These data explain the tendency for the aircraft to weathercock into the wind when braking on slippery runways in crosswinds. The deceleration trace in figure 6(b) indicates that tire friction improved as the aircraft speed decreased. (Also, see fig. A1(b).) This trend was characteristic of all wet runways

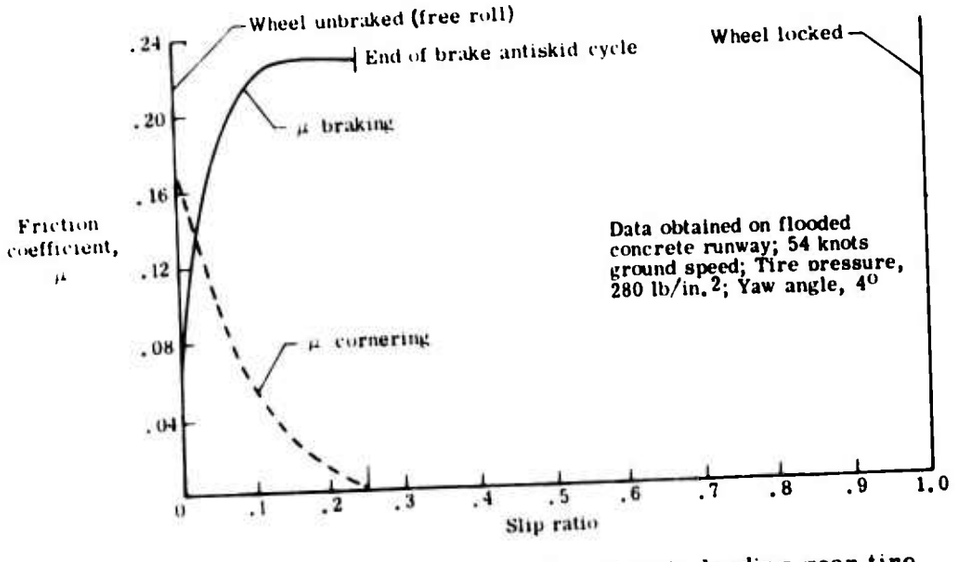


Figure 9.- Loss of cornering friction of main landing gear tire of fighter aircraft.

except for the deeply grooved and porous surfaces which showed no loss in effective friction coefficient with increasing aircraft ground speed.

The deceleration of the diagonal-braked test vehicle on wet runways under diagonal-braked conditions exhibited the same trend as observed for the aircraft, that is, the deceleration or tire friction increased with decreasing vehicle ground speed. This effect is shown in figure 8(b). This trend is characteristic of the friction losses associated with viscous hydroplaning. At low speeds both the rolling tire and the skidding tire have more time to break through the thin water film lying between the tire and pavement than at high speeds. Consequently, more and more adhesion of friction is regained between the tire and pavement as ground speed decreases.

Snow-, slush-, and ice-covered runway braking characteristics. The slipperiest runway conditions encountered by the C-141A aircraft in this investigation developed when the runways were covered with snow and ice. A typical time history of wheel brake pressure, velocity, and aircraft longitudinal deceleration is shown in figure 6(c) for the aircraft braking run at Loring Air Force Base for a glazed-ice- and snow-covered runway condition at 21° F. The time history indicates that the aircraft is in a more slippery condition (stopping distance ratio, 3.51) than for a wet runway (fig. A1(nn)). The antiskid system, although cycling the brake pressure at 3.5 cycles per second, allowed the wheel to spin down to practically locked-wheel conditions approximately 7 seconds after brake application. This trend indicates that the aircraft would weathercock in a crosswind. The aircraft during the Loring braking run was exposed to a direct crosswind component of approximately 6 knots and developed $6\frac{1}{2}^{\circ}$ yaw into the wind. The pilot used aerodynamic controls and nose-wheel steering and had no problem maintaining directional control during the braking stop. In contrast to the wet-runway trends in which the tire friction coefficient increases as ground speed is decreased, the deceleration data in figure 6(c) indicates that on snow and ice, the friction coefficient tends to be either constant with speed or to decrease slightly with decreasing ground speed.

The nose-wheel steering on the C-141A aircraft was very effective on snow- and ice-covered runways for small nose-wheel steering angles. The fact that nose-wheel steering is lost at larger steering angles was encountered after a landing on the snow- and ice-covered runway at Glenview Naval Air Station. The landing was accomplished without any directional problems. However, it took extensive maneuvering to turn the aircraft from the runway onto the taxiway because the nose wheel would slide instead of turning the aircraft at the large steering angle required. The turn was finally accomplished by the use of asymmetrical forward and reverse thrusts from the engines.

The diagonal-braked test vehicle exhibited braking characteristics on snow and ice similar to those for the C-141A aircraft. This effect is illustrated in figure 8(c) from the time history for the braked run for the vehicle at Loring Air Force Base and on glazed ice

and snow in figure A1(nn). On most of the snow- and ice-covered runways, a definite trend for the skidding tire friction coefficient to decrease with decreasing ground speed was evident. In fact, the lowest skidding friction coefficients measured were just before the vehicle came to a complete stop. It is felt that this result was caused by the skidding tires having more time at lower speeds to pressure melt the surface of the snow or ice in the ground contact areas and thus create a water film for the tires to slide on.

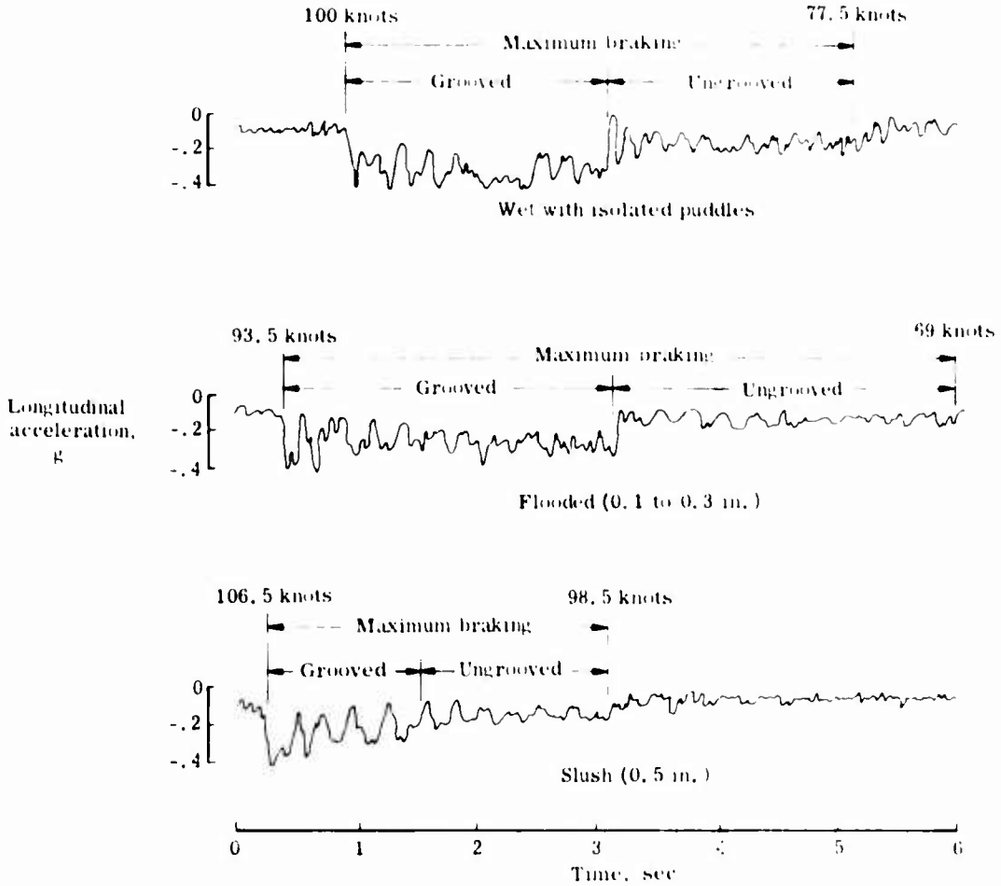
The test vehicle driver had little difficulty maintaining directional control of the diagonal-braked vehicle during braking tests on the slipperiest snow and ice-covered runways tested as long as he used small steering wheel inputs. Steering capability was also lost for the vehicle as was just described for the aircraft when large steering angles were applied. The most difficulty experienced by the vehicle on snow and ice was accelerating up to the test speed of 60 miles per hour. For this low friction condition, the driver had difficulty applying proper throttle to allow the vehicle to accelerate without spinning the rear wheels with subsequent "fishtailing" or "spin out." Acceleration distances required to obtain 60 miles per hour on snow and ice were as much as 4000 to 5000 feet.

Limited Braking Tests at Wallops Landing Research Runway

Since extensive braking tests had already been conducted for aircraft (ref. 1) under simulated all-weather test conditions on the landing research runway, it appeared advantageous to perform similar tests for the C-141A aircraft to provide a comparison of braking characteristics with the previous test aircraft. The landing research runway at NASA Wallops Station (shown schematically in fig. C1) is composed of level test sections which exhibit surface and composition differences. Also provided are removable dams for the retention of surface wetness conditions. Pavements with surface finish and composition differences were installed with grooved and ungrooved sections. A complete description of the landing research runway may be found in reference 1.

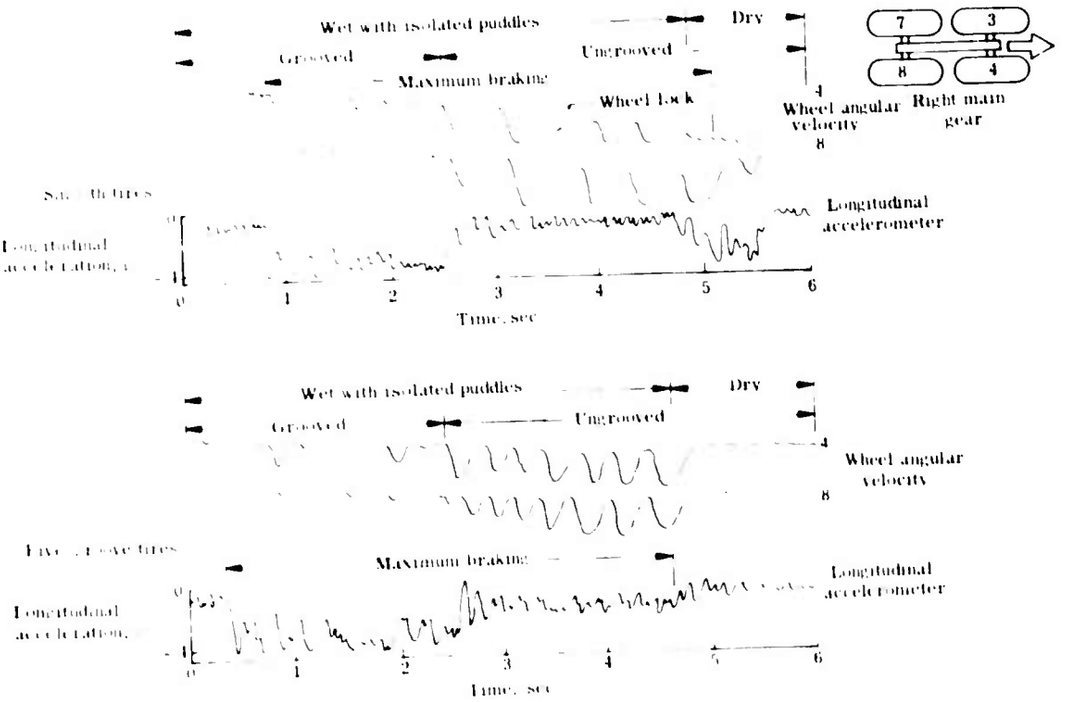
Effects of grooving.- The effects of 1/4 inch by 1/4 inch by 1 inch pitch grooves on C-141A longitudinal deceleration and main-gear wheel velocity in raw data format are shown in figure 10. Figure 10(a) shows considerable deceleration gains in the concrete test region containing 1/4 inch by 1/4 inch by 1 inch pitch grooves as compared with the otherwise similarly prepared ungrooved surface for wet and puddled, flooded, and slush-covered conditions. These maximum antiskid braking runs were conducted over limited test-section lengths on the landing research runway at speeds near those for normal-landing brake engagement.

Comparisons of braking coefficient data on dry surfaces and on wet and puddled surfaces for three of the aircraft tested on the landing research runway are shown in figure 11. The friction coefficients for the C-141A on a dry surface increases with increasing velocity (fig. 11(a)) whereas the friction coefficients for the 990A (fig. 11(b))



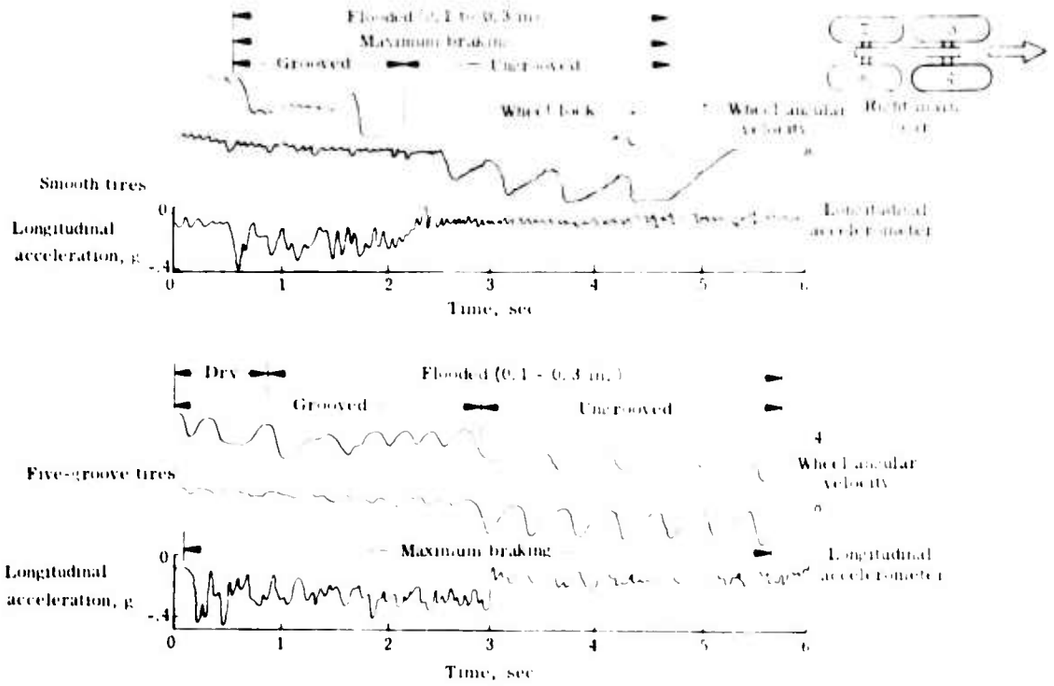
(a) General trends.

Figure 10.- Effects of grooving on raw data time histories.



(b) Tread effects (wet).

Figure 10.- Continued.



(c) Tread effects (flooded).

Figure 10.- Concluded.

and the F-4D (fig. 11(c)) decrease with increasing velocity. This difference in dry braking effectiveness levels is attributed, as was previously noted, for full-stop braking test results, to C-141A antiskid efficiency losses in the lower speed range rather than to brake fade.

The friction coefficient data obtained from the C-141A tests on the original nine surfaces of the landing research runway surfaces (A to I) for wet and puddled test conditions resulted in a relative slipperiness rating of the surfaces which was consistent with results obtained for the 990A and F-4D (parts (b) and (c) of fig. 11). The most significant result which is once more very much in evidence is the increase in C-141A braking effectiveness under wet and puddled conditions attributable to 1/4 inch by 1/4 inch by 1 inch pitch transverse grooving; that is, compare grooved surface data for surfaces H, G, C, and B with results obtained from the similar textured and wetted ungrooved surfaces I, F, D, and A. The gripstop surface E also provides some improvement in braking effectiveness for the wet and puddled tests.

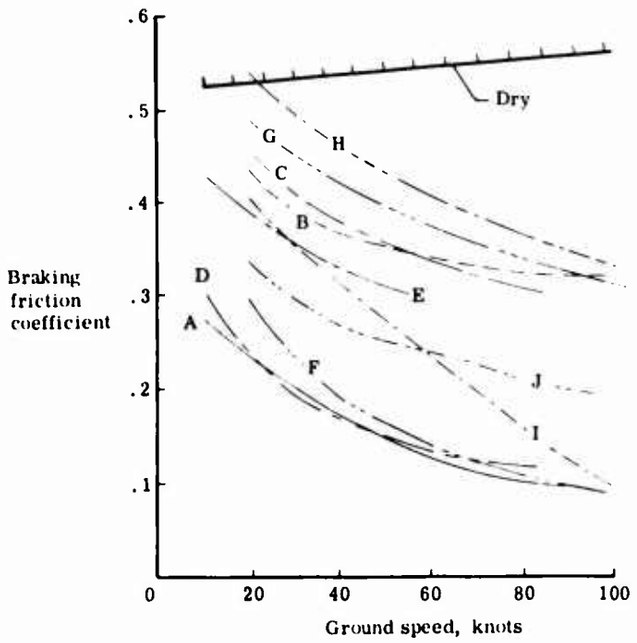
Surface J which was added to the landing research runway test surface after completion of the 990A and F-4D test programs exhibits a grooved surface similar to the Seymour Johnson Air Force Base runway groove configuration (1/4 inch by 1/4 inch by 2 inch pitch grooves for 2 feet followed by 2 feet of ungrooved concrete). A comparison of C-141A wet and puddled braking effectiveness data obtained on surface J is made in figure 12 with similarly obtained data from a 1/4 inch by 1/4 inch by 1 inch concrete surface (representative of the Beale Air Force Base runway configuration) and an ungrooved concrete surface. The Seymour Johnson groove configuration provides considerable improvement in braking friction coefficient over the ungrooved concrete surface; however, the continuous 1/4 inch by 1/4 inch by 1 inch pitch configuration provides a further increase in braking effectiveness over the speed range investigated for wet and puddled concrete surfaces. It is of further interest to note that full-stop braking test results on the Seymour Johnson Air Force Base runway provided higher friction coefficients for the surface in a damp or wet condition (fig. A1(m)) than the tests on the same configuration on the landing research runway at the NASA Wallops Station. This difference is attributed to the drainage capability of the Seymour Johnson runway provided by the grooving with transverse slope, whereas a more uniform wetness condition was maintained during the level surface tests on the landing research runway.

The comparison of flooded grooved and ungrooved surfaces (fig. 13) indicates that the C-141A, as did the 990A and F-4D, achieved significantly higher braking friction coefficients on grooved as opposed to ungrooved surfaces. Surface E, the gripstop asphalt surface, affords slight improvements in braking effectiveness over ungrooved asphalt (surface F) at high speed $\left(V_G \approx 80 \text{ to } 100 \text{ knots}\right)$ under flooded conditions.

Path-clearing effects.- The effects of forward-tire path clearing for the C-141A twin-tandem main gear bogies are shown by comparing figures 10(b) with 10(c). The

Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
B	Concrete	Canvas belt	1 in. by 1/4 in. by 1/4 in.
C	Concrete	Burlap drag	1 in. by 1/4 in. by 1/4 in.
D	Concrete	Burlap drag	Ungrooved
E	Asphalt	Gripstop	Ungrooved
F	Asphalt	Small aggregate	Ungrooved
G	Asphalt	Small aggregate	1 in. by 1/4 in. by 1/4 in.
H	Asphalt	Large aggregate	1 in. by 1/4 in. by 1/4 in.
I	Asphalt	Large aggregate	Ungrooved
J	Concrete	Burlap drag	2 in. by 1/4 in. by 1/4 in.

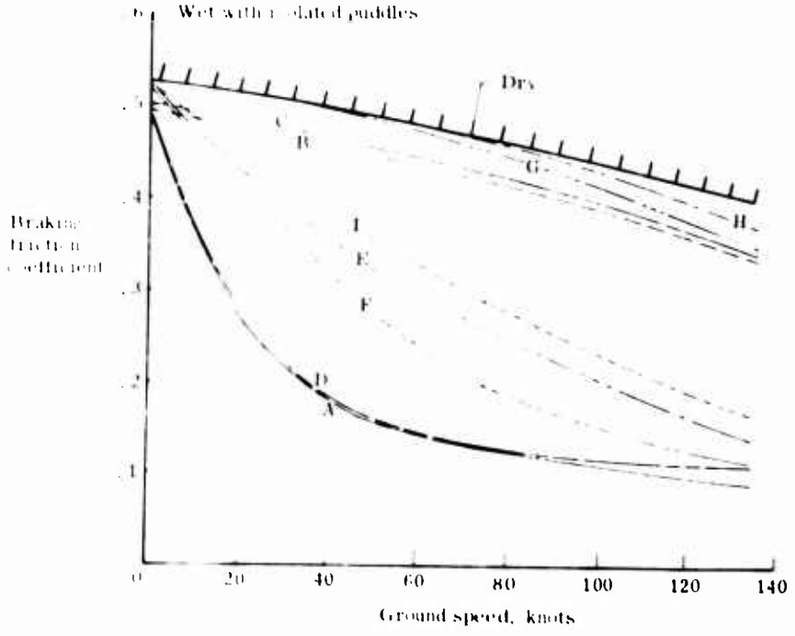
(Seymour Johnson AFB groove configuration)



(a) C-141A.

Figure 11.- Comparison of braking friction coefficients on wet and puddled runways obtained for three aircraft.

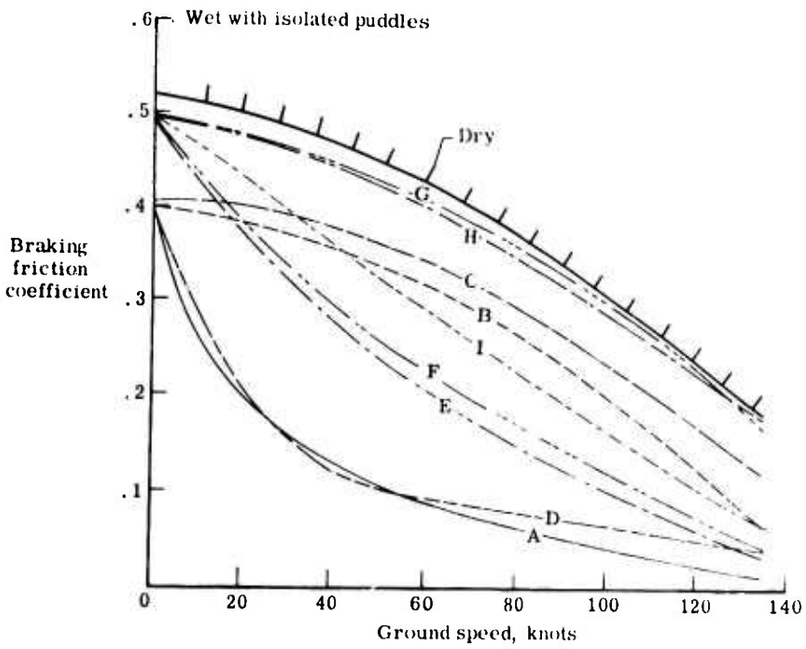
Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
B	Concrete	Canvas belt	1 in. by 1 4 in. by 1/4 in.
C	Concrete	Burlap drag	1 in. by 1 4 in. by 1 4 in.
D	Concrete	Burlap drag	Ungrooved
E	Asphalt	Gripstop	Ungrooved
F	Asphalt	Small aggregate	Ungrooved
G	Asphalt	Small aggregate	1 in. by 1 4 in. by 1 4 in.
H	Asphalt	Large aggregate	1 in. by 1 4 in. by 1 4 in.
I	Asphalt	Large aggregate	Ungrooved



(b) 990A.

Figure 11.- Continued.

Surface	Material	Treatment	Grooves
A	Concrete	Canvas belt	Ungrooved
B	Concrete	Canvas belt	1 in. by 1 4 in. by 1 4 in.
C	Concrete	Burlap drag	1 in. by 1 4 in. by 1 4 in.
D	Concrete	Burlap drag	Ungrooved
E	Asphalt	Gripstop	Ungrooved
F	Asphalt	Small aggregate	Ungrooved
G	Asphalt	Small aggregate	1 in. by 1 4 in. by 1 4 in.
H	Asphalt	Large aggregate	1 in. by 1 4 in. by 1 4 in.
I	Asphalt	Large aggregate	Ungrooved



(c) F-4D.

Figure 11.- Concluded.

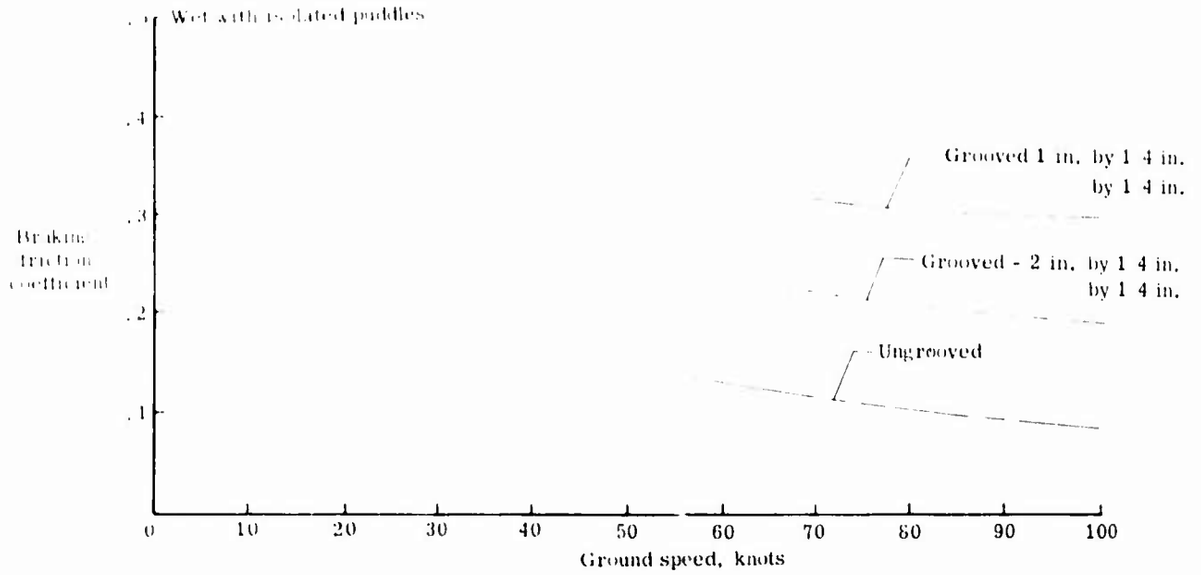
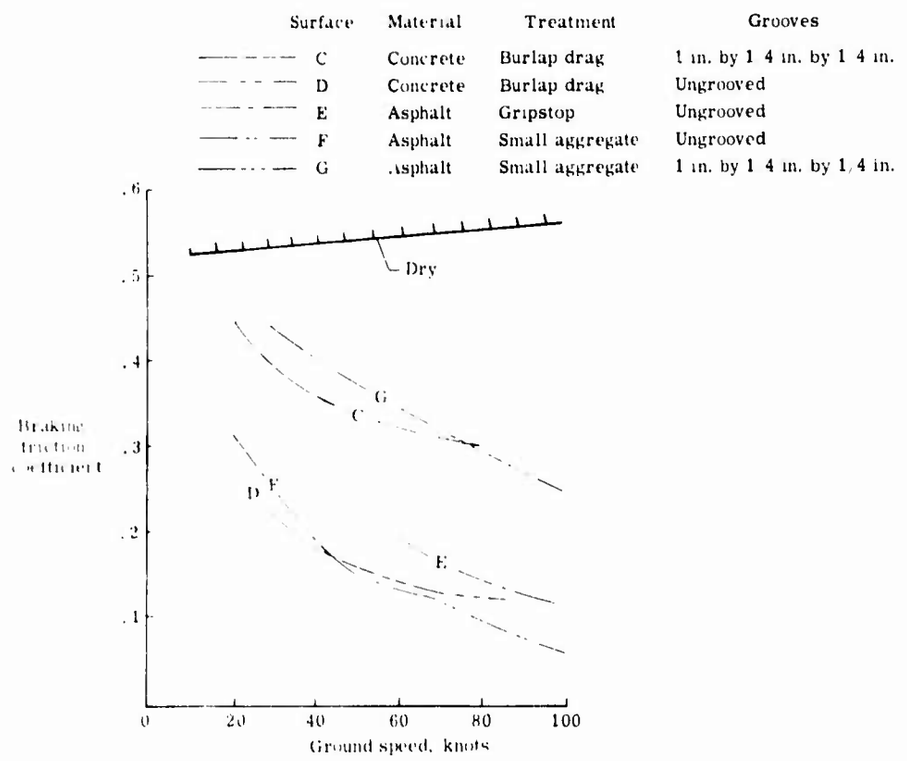
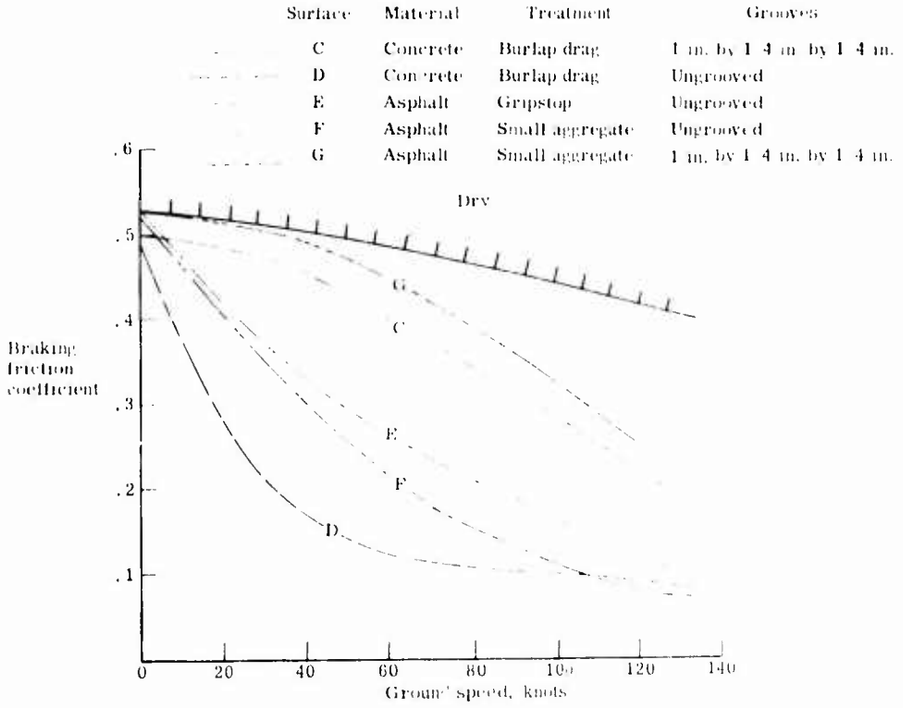


Figure 12.- Effect of runway groove configuration on C-141A aircraft braking on landing research runway at NASA Wallops Station.

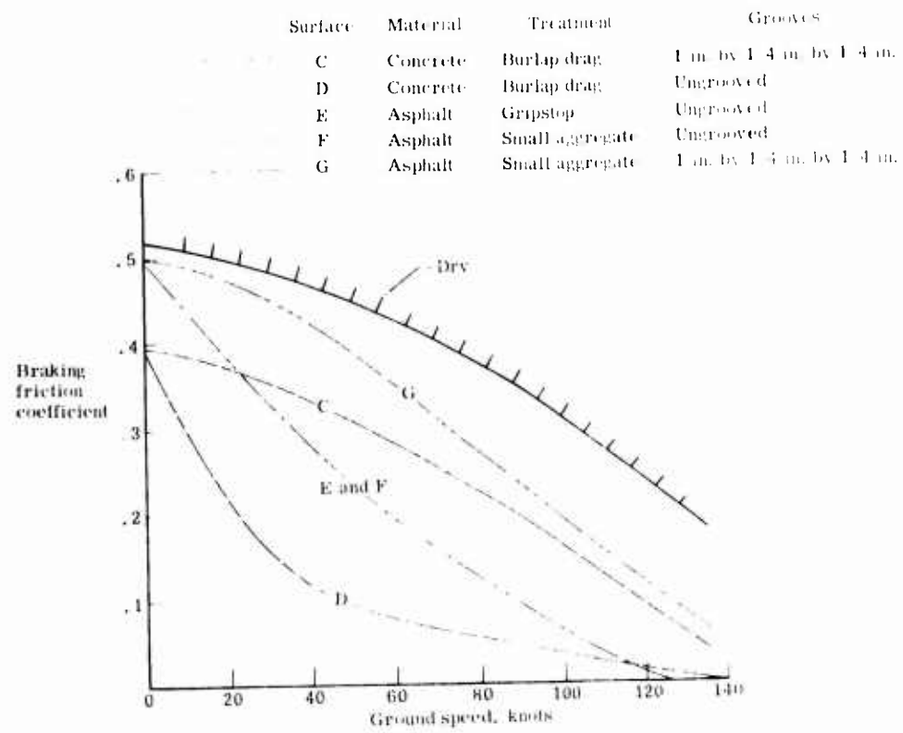


(a) C-141A.

Figure 13.- Comparison of braking friction coefficients on flooded runways (0.1 in. to 0.3 in. water depth) for three aircraft.



(b) 990A.



(c) F-4D.

Figure 13.- Concluded.

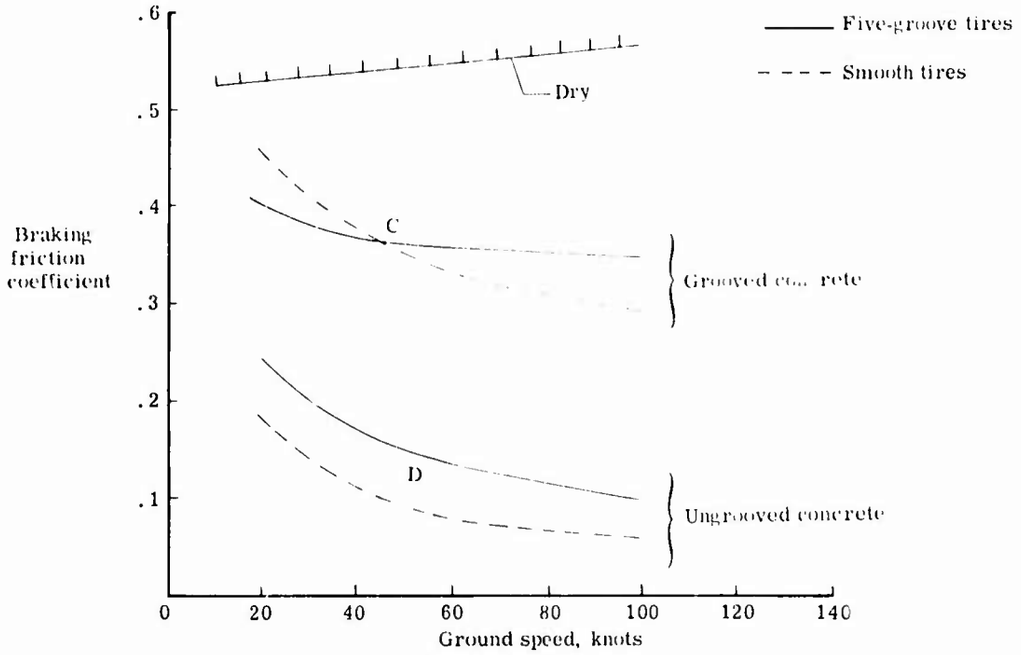
trailing-wheel spindown characteristics, represented by trace 8, on the two figures are noted to be similar on flooded and wet test surfaces. This observation emphasizes the desirability of the path clearing of the forward bogie wheels (and, therefore, the twin-tandem or a tandem bogie design) since the rear tires appear to be operating in a wet and puddled braking environment on a flooded runway.

Effects of tire-tread design.- Some effects of tire-tread design are shown in figures 10(b) and 10(c) for comparative C-141A braking runs with either smooth or five-groove tires on wet with isolated puddles and flooded concrete surfaces. More prolonged wheel lockups are noted to occur for the smooth-tread tires operating on the wet-ungrooved surface (top right of fig. 10(b)) as compared with the five-groove tire tread on the same wet surface (bottom right of fig. 10(b)). As a result, a loss in longitudinal deceleration (hence, braking effectiveness) is noted for the C-141A equipped with smooth tires. However, when comparing the smooth and five-groove tire braking characteristics on the wet grooved concrete surface (left half of fig. 10(b)), no appreciable tire spindowns or losses in airplane deceleration are observed. This result indicates that pavement grooving is an effective way to minimize the braking losses that normally occur between new and worn aircraft tires on wet-runway surfaces. Figure 10(c) shows the braking characteristics of both smooth and five-groove tires on flooded ungrooved and grooved concrete pavements. As indicated by comparing the velocity traces for the forward wheels (trace 4), more prolonged spindowns (or lockups) are noted to occur for the smooth forward tire than for the forward five-groove tire (bottom of fig. 10(c)) on both the ungrooved and grooved flooded concrete pavements.

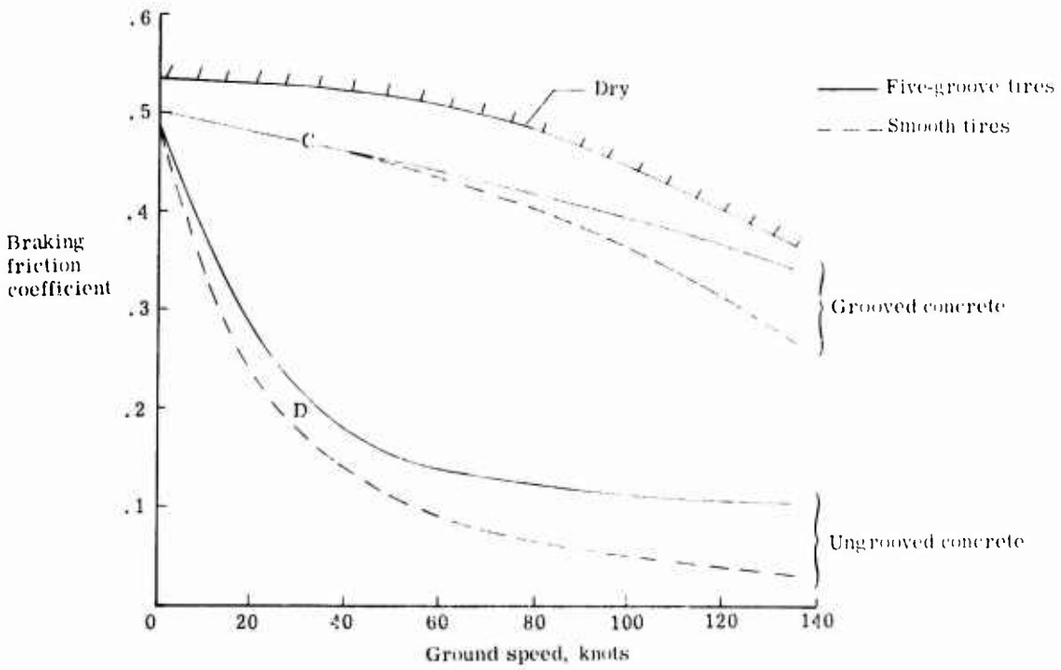
The comparative braking effectiveness of smooth and five-groove tires on wet and puddled surfaces is shown in figures 14(a) and 14(b) for the C-141A and 990A, respectively. These comparisons for operations on ungrooved pavements indicate considerable gains in braking effectiveness levels using five-groove tires as compared with smooth tires (simulated worn tires) for both aircraft. Calculations made in reference 1 indicate that the losses in braking effectiveness for the smooth-tire condition just shown increases the stopping distance of the 990A aircraft on the wet ungrooved concrete runway approximately 1500 feet over that required for the unworn five-groove tire design. No significant losses in braking effectiveness are noted between five-groove and smooth-tire braking operations on wet-grooved surfaces for either aircraft. (See fig. 14.) Therefore, no significant increases in stopping distance would be expected for smooth or worn tire operations on the wet-grooved surface.

Aircraft and RCR Correlation

Wet and flooded runways.- The 1968 NASA and Air Force studies at Wallops Station (ref. 1) indicate that very poor correlation existed between aircraft stopping distance



(a) C-141A.



(b) 990A.

Figure 14.- Tire-tread effects on wet and puddled runways for twin-tandem bogie arrangements.

measurements and runway condition readings (RCR) for the nine runway surfaces studied under wet and flooded conditions as shown in figure 15. A similarly poor correlation was also found in the present investigation where C-141A stopping distance and RCR measurements were obtained on 36 runways under artificially or naturally wet conditions as shown in table I and figure 16. A statistical analysis of the data of figure 16 was made and the line through the point 1, 1 with least mean square error had a slope of 2.809. The root mean square error in the aircraft stopping distance ratio was 0.56 about this line. The deviation about the line of perfect agreement is much greater. The results just described indicate that RCR measurements made on wet runway surfaces with the James brake decelerometer can considerably underestimate aircraft stopping performance.

Snow-, slush-, and ice-covered runways.- The limited tests conducted on snow-, slush-, and ice-covered surfaces show much better correlation between the C-141A and the RCR vehicle. In fact, instead of underestimating aircraft performance, as the RCR was found to do on wet runways, the RCR system on snow- and ice-covered pavements, overestimated aircraft stopping performance. (See fig. 16.) The RCR system thus yields a conservative result when used to predict aircraft performance on snow- and ice-covered runway surfaces. It is important to note that a relatively narrow range of snow and ice temperatures was included in this investigation (8° F to 33° F).

Comments on the RCR system.- The data obtained from aircraft and ground vehicles during the present investigation offer an explanation for the unconservative performance of the RCR system in predicting aircraft stopping capability on wet runways and the conservative performance of the RCR system on snow- and ice-covered runways. The RCR system has a James brake decelerometer (damped pendulum instrument) installed securely on the floor of the front part of an airport ground vehicle, usually a station wagon. The brakes of the vehicle are firmly applied until all four wheels are fully locked at a ground speed ranging between 20 and 30 miles per hour on the runway to be tested. The maximum reading of the instrument, which is the deceleration in ft/sec^2, is noted; this value is the RCR number. The vehicle must be equipped with standard or snow tires in good repair. The standard tires just described have an efficient tread design for improving tire traction on wet pavements. At a vehicle speed of 20 to 30 mph, it can be expected on wet pavements that the vehicle performance will be influenced more by tire-tread design than by the basic runway slipperiness. As a further example of this point, consider the data shown in figure A1(h) for the Lockbourne Air Force Base wet concrete runway. At a ground speed of 20 knots, there is little difference between the aircraft wet and dry friction coefficients (lower part of fig. A1(h)); this result is the same as that indicated by the RCR vehicle at approximately the same speed, 23 dry and 22.5 wet. However, it will be noticed that at high speeds (up to 100 knots), the wet runway is very slippery to the aircraft as indicated by the much lower friction coefficients obtained. This condition results in a relatively high stopping distance ratio (2.05) which

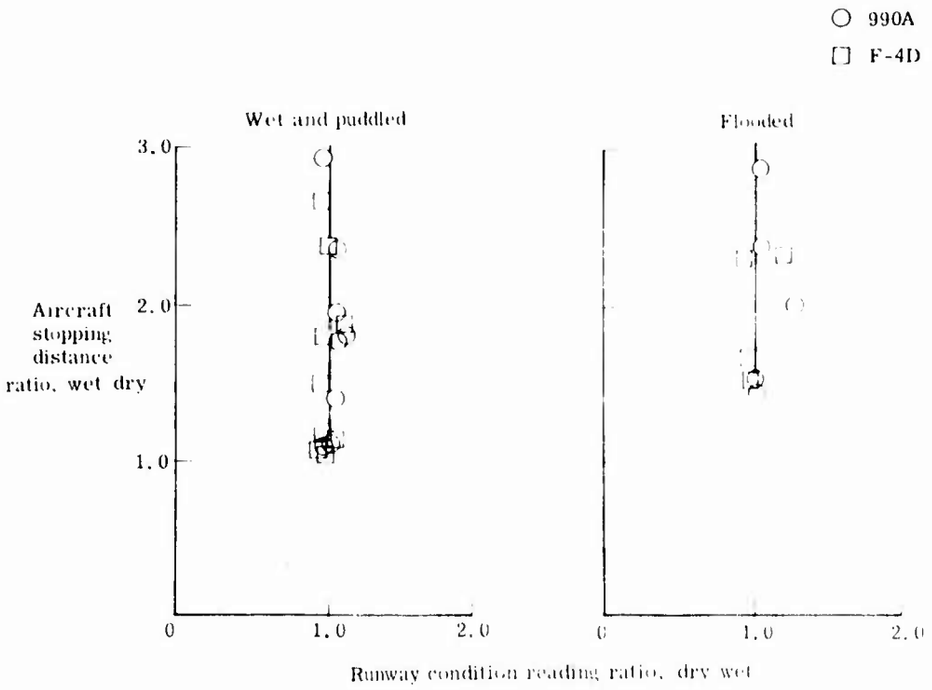


Figure 15.- Comparison of aircraft stopping distance ratios with RCR ratios. Vehicle test conditions: velocity, 30 mph; four-wheel skid; typical production tires; tire pressure, 24 lb/in^2; tire vertical load, 1012 lb (1968 NASA-Air Force Study, ref. 1).

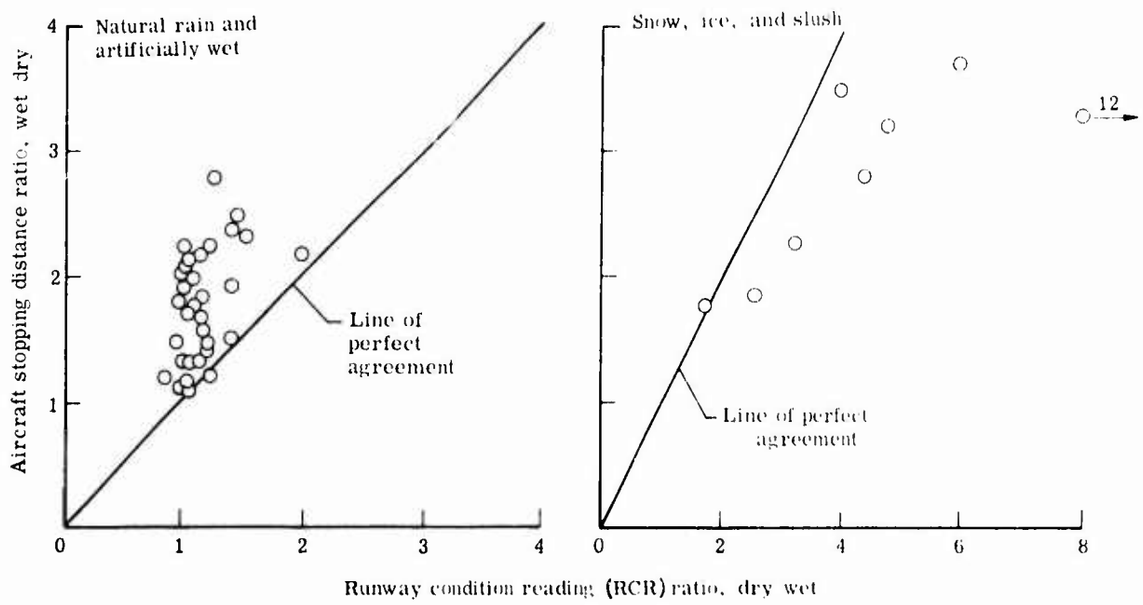


Figure 16.- Correlation between C-141A aircraft and RCR test vehicle.

contrasts with the RCR measurements that were made at the lower speed and indicated essentially a dry-runway condition (23 dry and 22.5 wet).

NASA research on viscous hydroplaning (ref. 9) indicates that the smoother the pavement surface the greater the tire friction loss to viscous hydroplaning and the less effective tire-tread design becomes. The most perfect example of viscous hydroplaning is a tire braking on wet glare ice. For this condition no difference in friction level can be detected between tires with smooth-tread (bald) or brand new rib-tread tires. The smooth-textured runway surface at Dyess Air Force Base (fig. A1(a)) approaches this condition when wet. It can be seen that the aircraft indicated the runway as slippery with a stopping distance ratio of 2.77. The RCR ratio measured for the runway was 1.28. The correlation between the aircraft and RCR vehicle is poor for this runway, but it can be seen that the RCR is reporting the runway more slippery when wet than when dry.

On snow- and ice-covered runways, the situation is very different. The aircraft results on the glazed-ice- and snow-covered runway at Loring (see figs. 6(c) and A1(nn)) indicate that the effective aircraft friction coefficient is nearly constant with ground speed. Under diagonal braking, the tests were made with the NASA test vehicle with the diagonal pair of smooth-tread tires locked and skidding on the runway. As discussed earlier in the paper, this operational condition resulted in the lowest snow and ice friction coefficients being obtained when the vehicle came to a stop. This low-friction result was attributed to the skidding tire having time at low speeds to melt the surface layer of the snow- and ice-covered pavement and provide additional friction-lowering lubrication. It is felt that the RCR vehicle locking its wheels at 20 mph is also in this pressure-melting condition. It can be seen from figure 6(c), that the C-141A follows a similar trend (see aircraft deceleration trace) when the wheels become fully locked at low speed (time 38 seconds). As can be seen from table II, the RCR dry-wet ratio reports the slipperiness of the runway as 4.0, a more conservative result than the wet-dry stopping ratio of 3.51 reported by the aircraft on the same surface.

Aircraft and NASA Diagonal-Braked Test-Vehicle Correlation

The development of the diagonal-braked test vehicle stopping distance as a means for rating runway slipperiness and estimating aircraft performance on slippery runways is described in references 14 and 18. In contrast to the RCR system which is proven to be not effective on wet surfaces, the diagonal-braked test vehicle technique correlates well with different aircraft for all runway surface conditions of wetness, slush, snow, and ice studied as shown in figure 17. A more detailed analysis of the correlation of the aircraft and diagonal-braked test vehicle obtained from test results of the present investigation is presented herein.

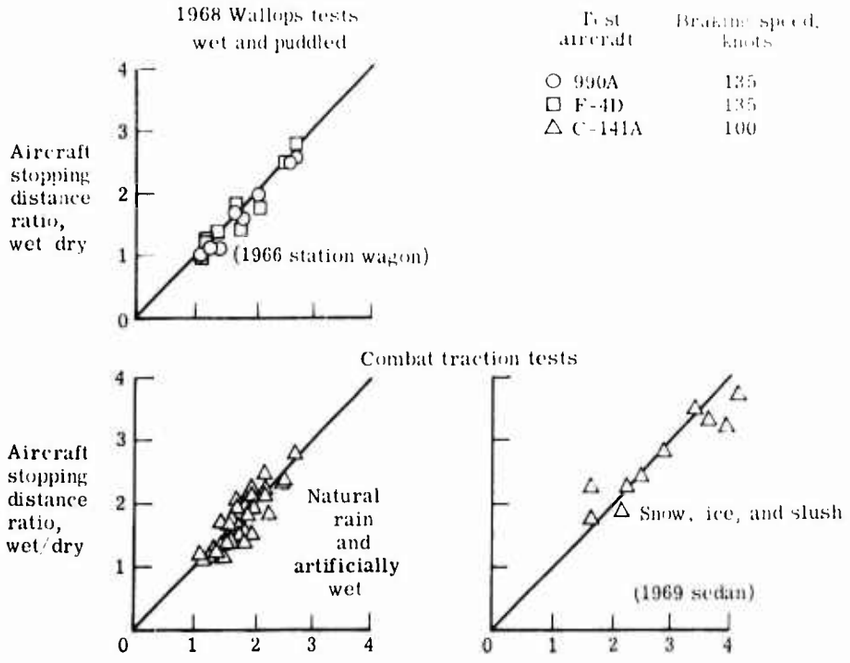
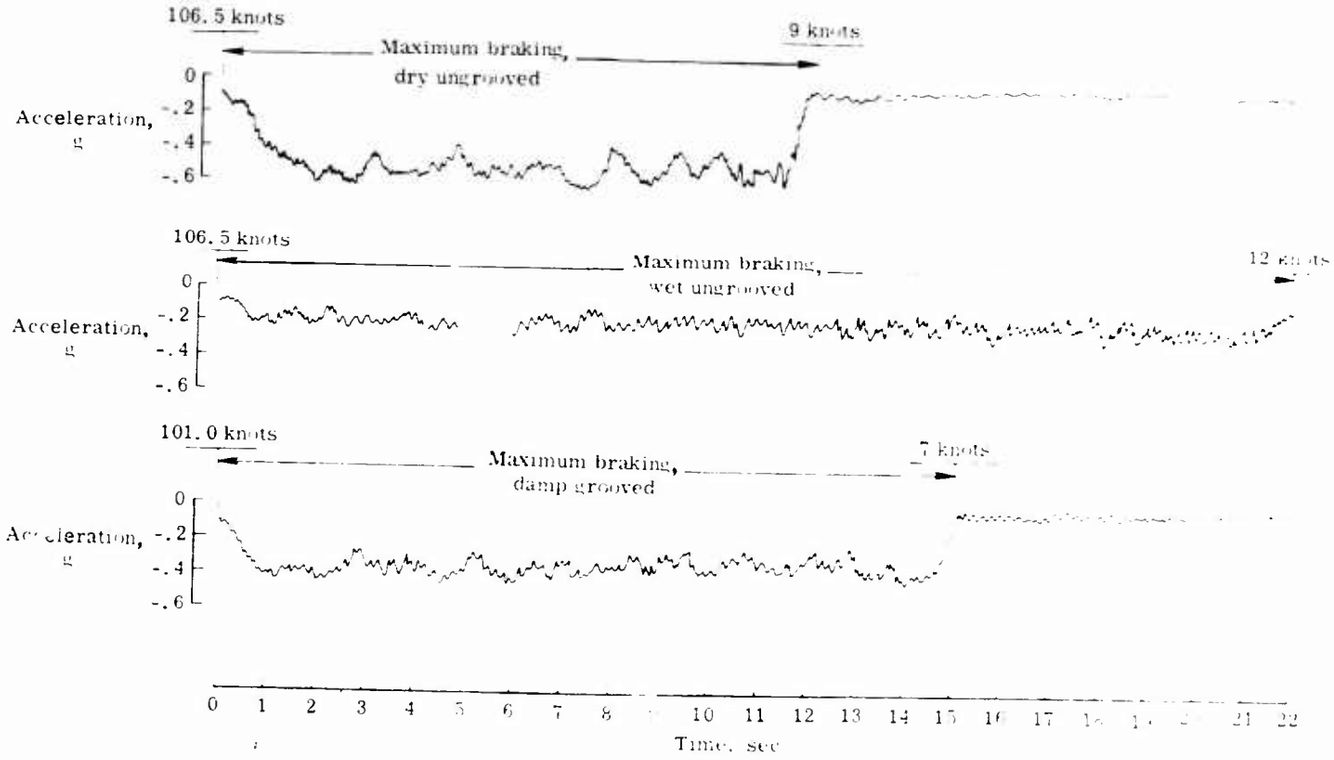


Figure 17.- Correlation between aircraft and test vehicle stopping distance ratios. The diagonal-braked test vehicle stopping distance ratio was determined by using a dry stopping distance of 302 feet for the snow, ice, and slush tests.

Artificially and naturally wet surfaces.- The manner in which the diagonal-braked test vehicle and the C-141A aircraft correlate in rating the slipperiness of pavement surfaces is illustrated by comparing the aircraft and test vehicle deceleration time histories obtained at Offutt Air Force Base and shown in figures 18(a) and 18(b), respectively. Wet and dry tests on the Offutt Air Force Base runway were conducted by the C-141A and test vehicle on September 10, 1969. These tests were repeated February 20, 1970, after the runway was transverse grooved to a $1\frac{1}{4}$ inch by 1/4 inch by 1/4 inch groove pattern. It can be seen from figure 17 that excellent correlation between the aircraft and the diagonal-braked test vehicle exists. Figure 19 and table I show the correlation obtained between the C-141A and the diagonal-braked test vehicle by using data from the present investigation obtained on 40 artificially wet or natural-rain-covered runways. The statistical analysis of the data of figure 19 with the line through the point 1,1 with least mean square error had a slope of 0.993. The root mean square error in the aircraft stopping distance ratio was only 0.19.

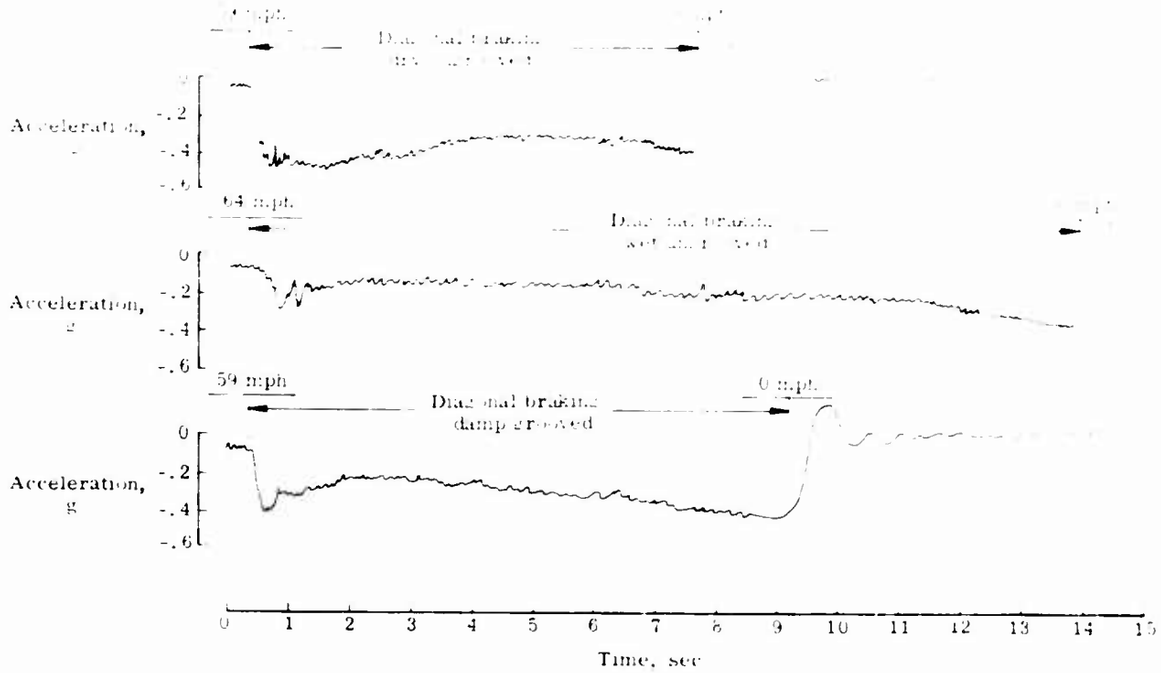
Snow-, ice-, and slush-covered surfaces.- Very good correlation between the C-141A aircraft and the diagonal-braked test vehicle was also found for the runways tested under slush, snow, and ice conditions as shown in figures 17 and 19 and table II. It should be pointed out that for both aircraft and test vehicle, dry stopping distance data were unobtainable because of the condition of the runways. Accordingly, the wet-dry stopping distance ratio for the aircraft was calculated by using an average dry stopping distance value of 1100 feet. The average stopping distance for all dry runs made by the diagonal-braked test vehicle in this investigation was 302 feet. The wet-dry stopping distance ratios used in figures 17 and 19 and table II for the test vehicle are based on this dry distance figure. It can be seen that on this basis, excellent correlation is achieved between the test vehicle and aircraft for snow-, ice-, and slush-covered runways.

The trend for the diagonal-braked test vehicle dry stopping distance to vary with ambient air temperature according to equation (1) as discussed earlier is of concern in this regard. The test vehicle wet-dry stopping distance ratios on slush, snow, and ice surfaces were recomputed by using the value of the test vehicle dry stopping distance obtained from equation (1) for the actual runway ambient air temperatures given in table II. The correlation between the test vehicle and the aircraft wet-dry stopping distance ratios on this basis is shown in figure 20. Also shown in the figure for comparison is the RCR dry-wet ratio obtained under the same conditions (from table II). It can be seen that for this case, the diagonal-braked test vehicle prediction of runway slipperiness is in agreement with the RCR method, and both ground vehicle methods overestimate aircraft stopping distance on slush-, snow-, and ice-covered runways. This result indicates the need for further correlation trials to be conducted between other aircraft and the diagonal-braked test vehicle on snow-, ice-, and slush-covered surfaces to determine



(a) C-141A aircraft.

Figure 18.- Braking at Offutt AFB on ungrooved and grooved runway surfaces under dry and wet conditions.



(b) Diagonal-braked test vehicle.

Figure 18.- Concluded.

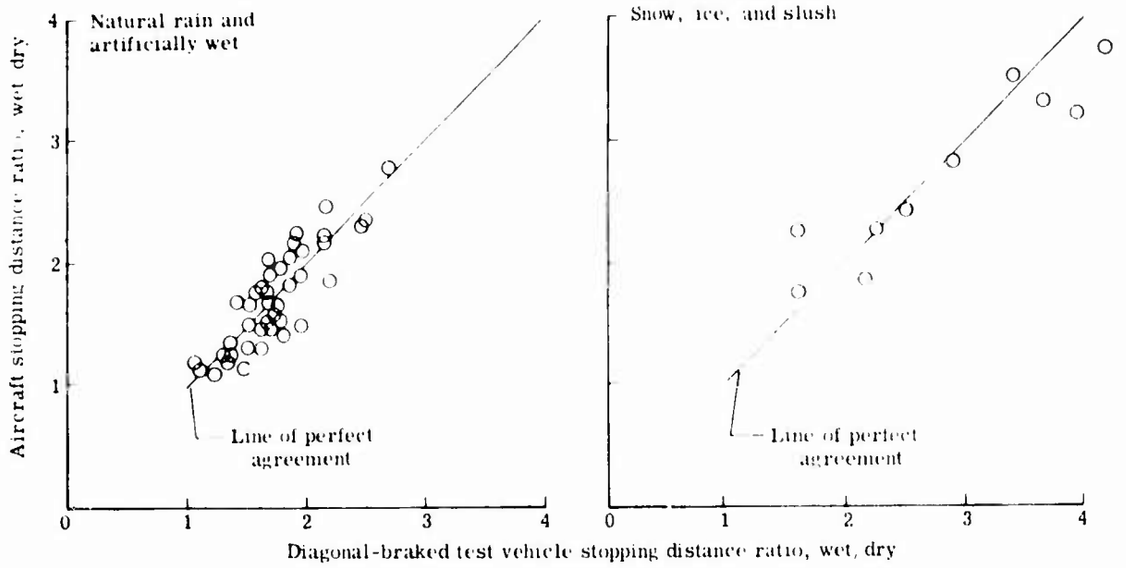


Figure 19.- Correlation between C-141A aircraft and the diagonal-braked test vehicle.

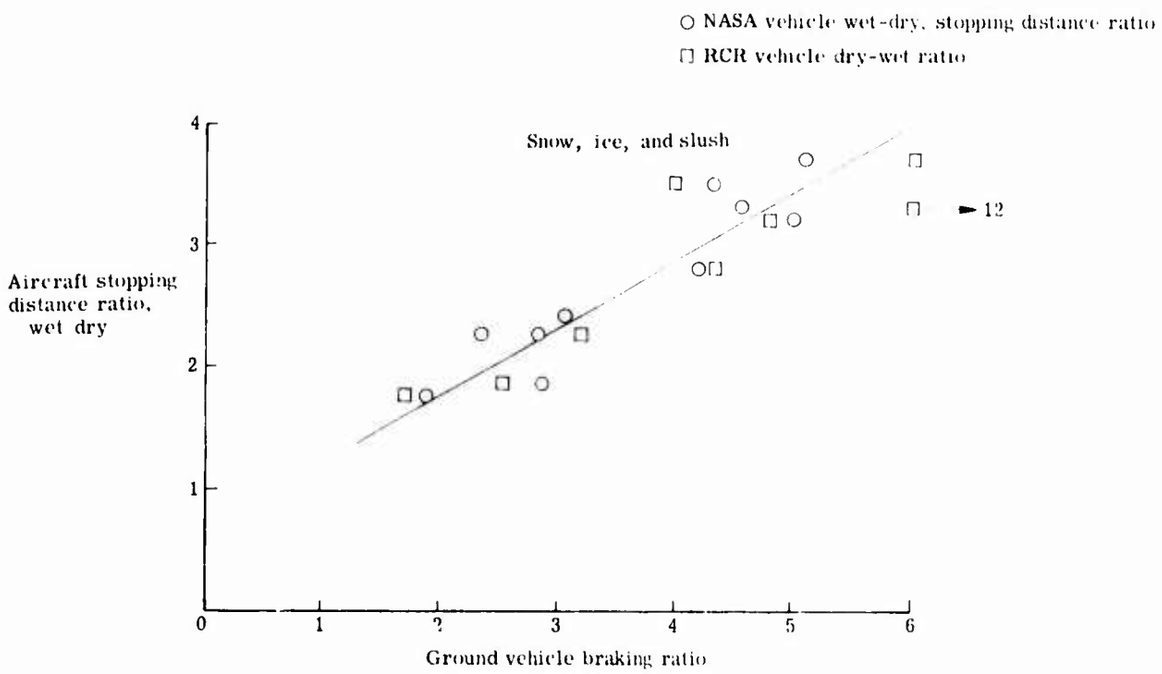


Figure 20.- Correlation between aircraft and ground vehicle braking ratio. Diagonal-braked test vehicle wet-dry stopping distance ratio based on dry stopping distance, $D_{vehicle,dry} = 208 + 145T_r$.

which dry stopping distance for the test vehicle (average dry value or temperature compensated) best agrees with aircraft stopping performance.

The correlation obtained between the C-141A and the diagonal-braked test vehicle on slippery runways can also be demonstrated by using data obtained with the auxiliary aircraft and test vehicle instrumentation used in the present investigation. For example, both the aircraft and test vehicle measured vehicle ground speed as a function of time. In figure 21, tire braking loss is computed from vehicle velocity time histories by using the relationship

$$\text{Braking loss} = \left\{1 - \frac{\left[\left(\frac{\Delta V}{\Delta t}\right)_{\text{Braked}} - \left(\frac{\Delta V}{\Delta t}\right)_{\text{Unbraked}}\right]_{\text{Wet}}}{\left[\left(\frac{\Delta V}{\Delta t}\right)_{\text{Braked}} - \left(\frac{\Delta V}{\Delta t}\right)_{\text{Unbraked}}\right]_{\text{Dry}}}\right\} \times 100 \qquad (2)$$

These data are plotted against vehicle wet-dry stopping distance ratios obtained from the test vehicle and aircraft by using revolution counter data for stopping distance. (See fig. A1.) A rather remarkable relationship is shown in figure 21. The 5000-lb test vehicle predicts the braking loss experienced by a 200 000-lb aircraft to within about ±10 percent accuracy at the larger (slipperier) wet-dry stopping distance ratios of interest. This relationship is of great importance since NASA research (ref. 1) shows little difference between tire braking and cornering (side-force) friction coefficients for similar wetness and speed conditions. Thus, figure 21 could be expressed as cornering traction loss as well as braking loss and thus could predict losses in tire steering and side-force capability necessary to estimate aircraft crosswind limitations on slippery runways.

It is felt that the technique described in this investigation to wet artificially a runway surface and obtain wet and dry diagonal-braked test vehicle stopping distances (wet-dry stopping distance ratio) within a short period of time (within 1 hour) has proven to be a reliable way to rate wet-runway slipperiness in terms of aircraft stopping performance. For example, the Edwards Air Force Base runway was tested by the test vehicle and aircraft on September 20, 1969. The test vehicle and aircraft developed wet-dry stopping distance ratios of 1.91 and 2.15, respectively. (See fig. A1(f).) This runway was retested by the test vehicle in June 1970. Under similar artificial wetting conditions (0.03-inch water depth), the test vehicle at this latter date developed a wet-dry stopping distance ratio of 2.10. It is of considerable interest to note that the dry stopping distance for the test vehicle was 269 feet in September 1969 and 316 feet in June 1970 even though the ambient air temperatures were approximately the same (58° F in September 1969 and 52° F to 64° F in June 1970). Preliminary data indicate that the diagonal-braked test

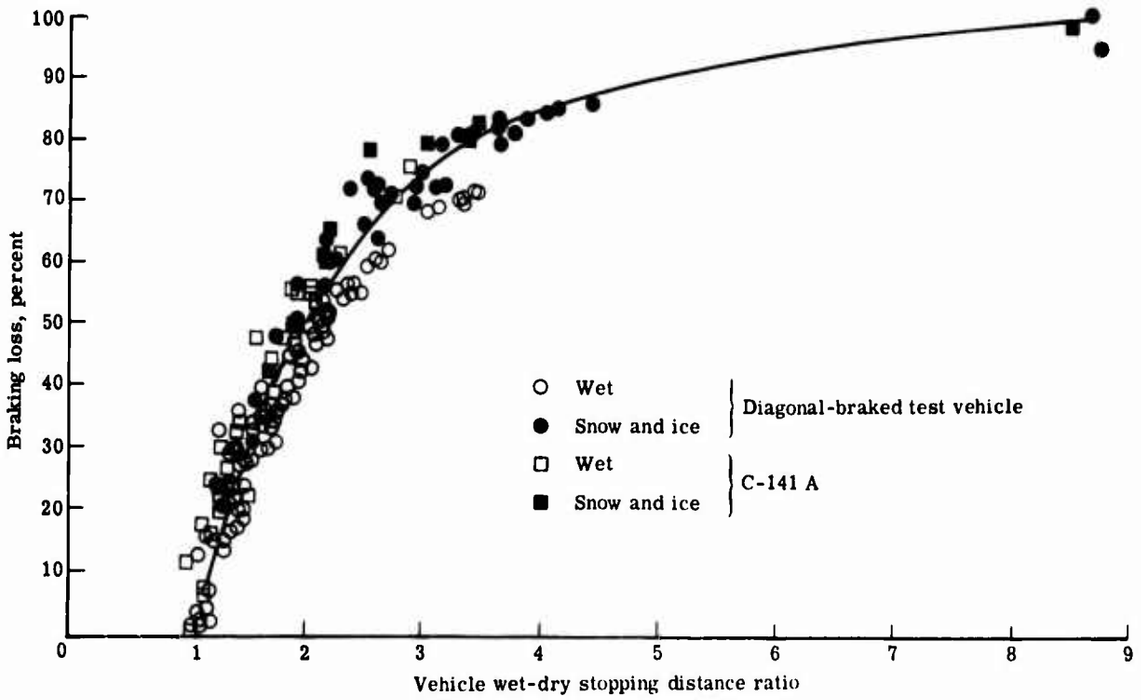


Figure 21. Effect of runway slipperiness on stopping distances and tire traction of C-141A aircraft and NASA diagonal-braked test vehicle.

vehicle achieved a reasonable correlation with the C-5A aircraft, test vehicle (2.09) and C-5A (1.88) for the runway wetted with a water-foam mixture. These results are encouraging because even though the test vehicle dry stopping distances varied considerably between tests at Edwards, the wet-dry stopping distances were reasonably close in magnitude.

When the diagonal-braked test vehicle is used operationally to predict aircraft performance at time of take-off and landing, it will most likely be impossible to make a test vehicle dry-runway stopping distance test in close time proximity to the wet-runway braking test. The question thus arises as to what value of the test vehicle dry-runway stopping distance should be assigned for the wet-dry stopping distance ratio. It is felt that the test vehicle wet- and dry-stopping distance measurements should be made on the same runway under similar artificial wetness conditions for a wide range of ambient air temperatures to answer this question properly for operational use.

A recent study made with the diagonal-braked test vehicle on a local airport runway during varying natural rain conditions (see fig. 22) indicates that the stopping distance ratio of the test vehicle increases with increasing rainfall precipitation rate and water depth on the runway. This result, although not unexpected, points out two areas of interest. First, the changing slipperiness of the runway with precipitation rate demonstrates the need to assess runway slipperiness at time of aircraft take-off and landing. Second, it has been proposed to correlate the diagonal-braked test vehicle stopping distance ratio with rainfall precipitation rate at a given airport runway. Once a correlation is established, the runway slipperiness condition during a rain can be determined from the rainfall precipitation rate without the need of making test vehicle stopping tests other than occasional calibration runs. This correlation would be of great help at busy airports. Also of interest in this figure is the fact that a 1.44-inch-per-hour precipitation rate produced an average water depth on the runway of 0.17. This depth is sufficient to produce aircraft hydroplaning. As discussed in the limited braking section of this paper, research is needed to determine the correlation of the diagonal-braked test vehicle with aircraft of different landing-gear wheel geometry on flooded runways because of wheel-path-clearing effects.

Equivalent RCR

As discussed earlier in the paper, U.S. Air Force aircraft flight manual take-off and landing distance charts are based on RCR numbers. This section of the paper develops a method for converting diagonal-braked test vehicle wet-dry stopping distance ratios to equivalent RCR values. These charts are constructed on the basis of a linear variation of RCR and aircraft braking coefficient as shown in sketch (a).

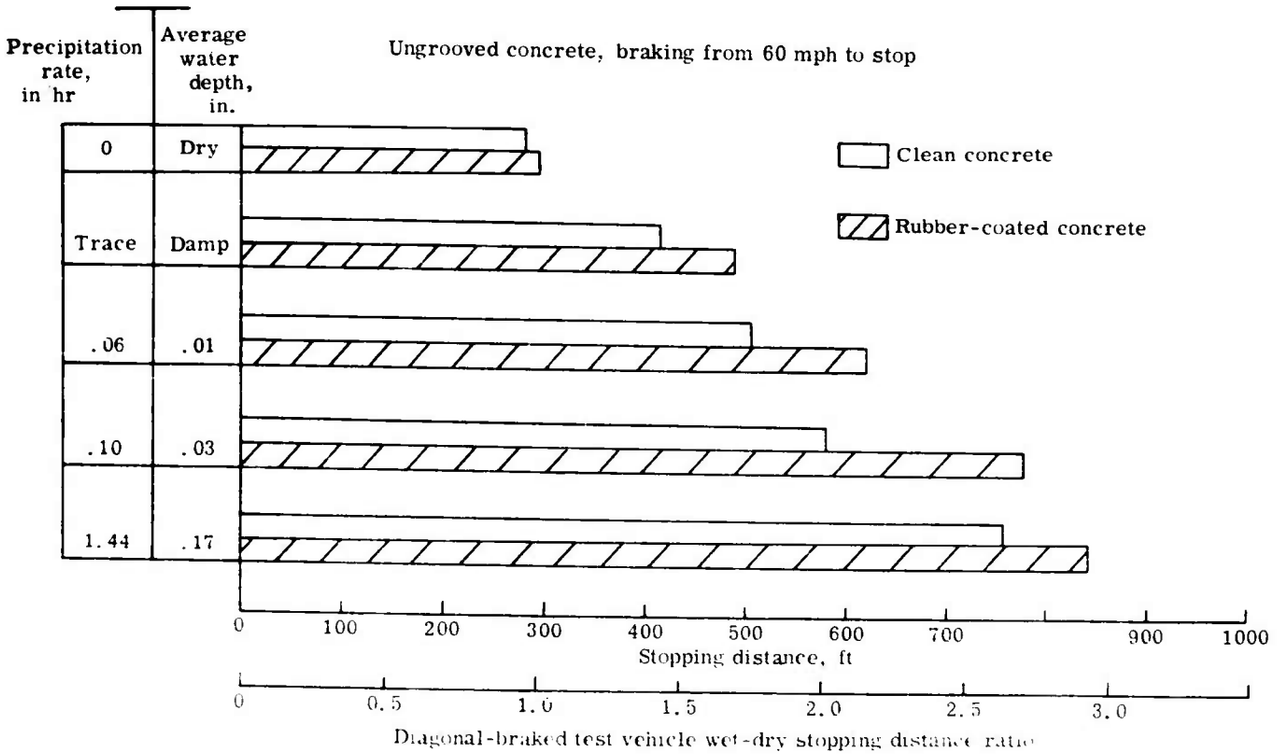
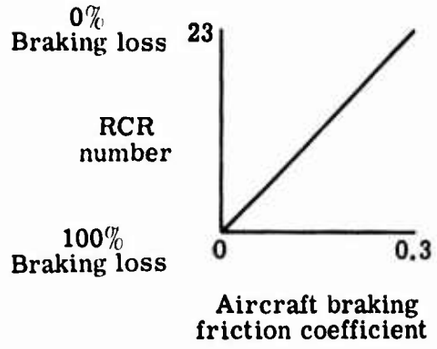


Figure 22.- Slipperiness of airport runway during natural rain.



Sketch (a)

For example, an aircraft during certification trials demonstrates an average braking friction coefficient of 0.3 during its dry-runway braking tests. The James brake-decelerometer-equipped vehicle during stops on dry runways usually develops an RCR number of 23. The landing distance chart for an RCR number of 11.5 is calculated on the basis of an average braking coefficient of 0.15. (See sketch (a).) The chart in figure 23 is developed by means of sketch (a) and figure 21 from which an equivalent RCR number can be obtained for a given vehicle wet-dry stopping distance ratio. This chart may be used for all aircraft whose flight manual RCR stopping distance data are developed according to the method outlined in sketch (a).

In September 1970, this conversion of stopping distance ratio to equivalent RCR was checked for the F-106 aircraft by the following procedure. Figure 24 describes a typical aircraft landing. The landing is composed of three segments; air distance, transition distance, and braking distance. The air distance is defined as the distance required for the aircraft to descend from a point 50 feet above the runway threshold to touchdown with the main landing gear. The transition distance is the distance required from touchdown to derotate the aircraft (nose-wheel touchdown) and apply wheel brakes. The braking distance is defined as the distance required to bring the aircraft to a stop after brake application. The total of the three segments is defined as the landing distance. Actually, only the dry braking distance is affected by runway surface slipperiness. A series of landings were made with the F-106 and the distance to brake application point from the runway threshold noted. This distance was subtracted from the aircraft flight manual landing distance (from threshold) to obtain dry stopping distance for the aircraft landing condition (gross weight). By using the procedure given in figure 25, it is possible to determine the average diagonal-braked test vehicle wet-dry stopping distance ratio $\overline{X}$ on a given runway from the aircraft brake application point. The diagonal-braked test vehicle was used to test the runway at Hamilton Air Force Base in September 1970. Preliminary data from this test indicates that runway 12 under a wet condition gave a stopping distance ratio of $\overline{X} = 2.15$. The dry distance for the F-106 obtained in the manner described earlier was multiplied by 2.15 to obtain the wet stopping distance for the aircraft on this runway. The

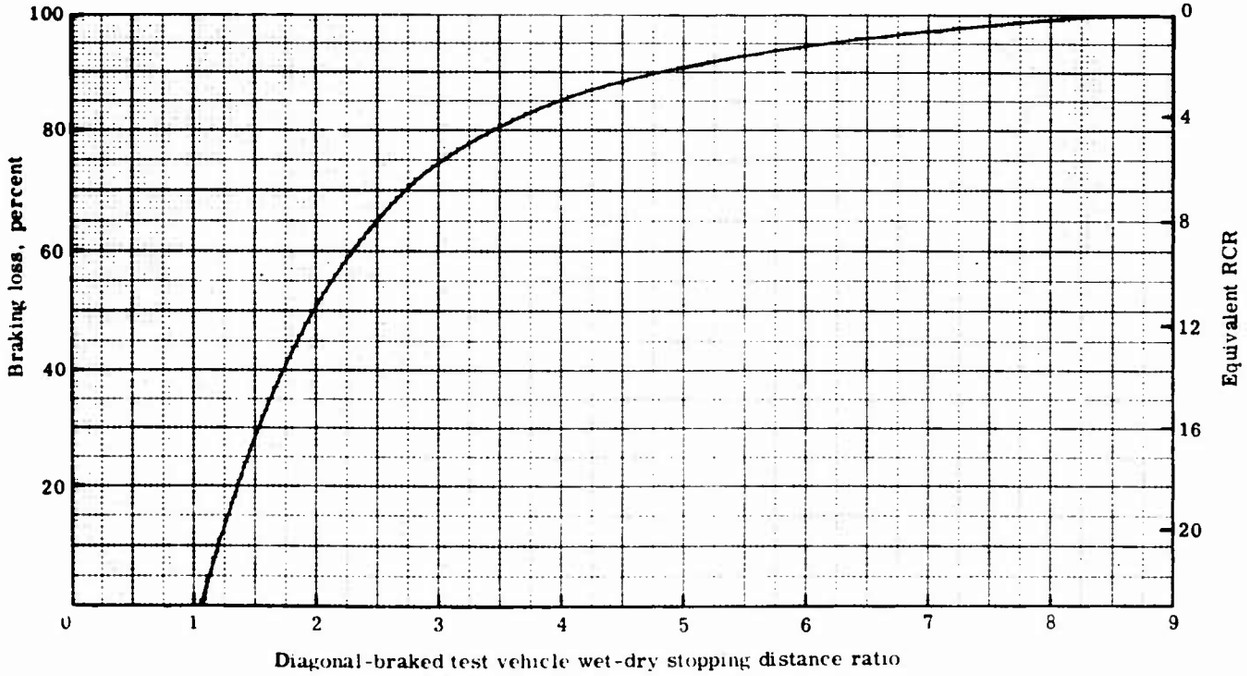


Figure 23.- Conversion of diagonal-braked test vehicle wet-dry stopping distance ratio to the equivalent RCR.

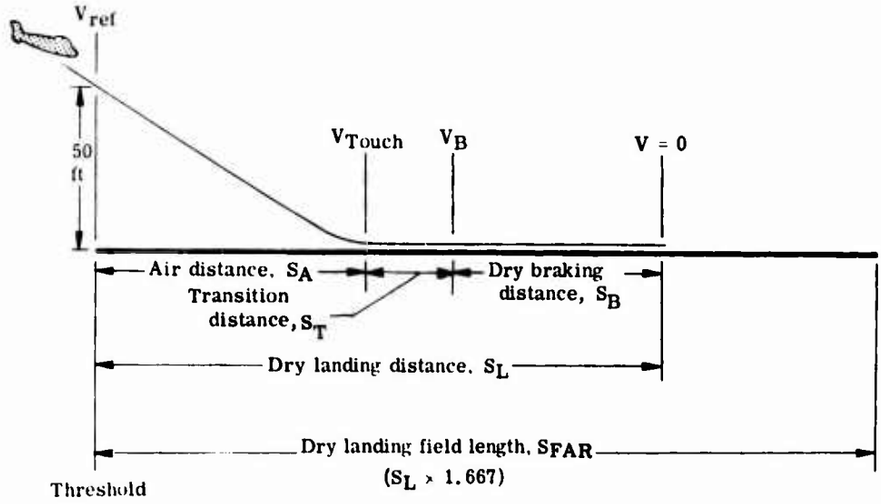


Figure 24.- Aircraft landing terminology.

NASA diagonal-braked test vehicle runway slipperiness measurements	
Runway location	Stopping distance ratio, wet/dry
Touchdown area; zone A, rubber coated	X_A
Braking area; zone B, clean	X_B
Rollout area; zone C, rubber coated	X_C

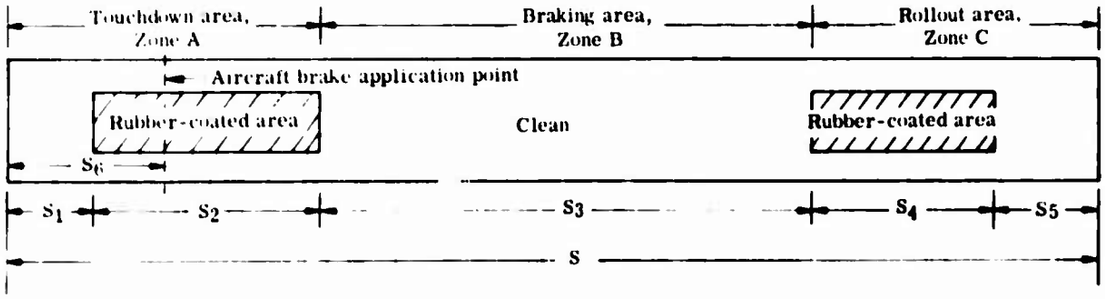


Figure 25.- Method for calculating the average diagonal-braked test vehicle wet-dry stopping distance ratio $\bar{X}$ for a given aircraft landing condition.

$$\bar{X} = \frac{(S_1 + S_2 - S_6)X_A + (S_3 + S_5)X_B + S_4X_C}{S - S_6}.$$

air distance and transition distance were then added to obtain the wet landing distance. This wet landing distance was entered into the flight manual at the aircraft landing condition to obtain an equivalent RCR of 11. The wet-dry stopping distance ratio of 2.15 obtained was entered in figure 23 to obtain an equivalent RCR of approximately 11.5. The agreement thus shown is very encouraging. However, operational use of the equivalent RCR method would depend upon further validation of the technique with other aircraft types.

British Ministry of Aviation Supply Evaluation of Runway Conditions

Two different British ground vehicle friction measuring devices, the friction meter (Mu-meter) and the Miles engineering skid trailer, were tested concurrently with the C-141A aircraft, RCR vehicle, and diagonal-braked test vehicle at all British Royal Air Force and Naval Bases studied in this investigation. The British Ministry of Aviation Supply report describing the Mu-meter and RCR vehicle evaluation of runway slipperiness at these bases is given in appendix D. The Ministry of Aviation Supply report did not present an evaluation of the runway surfaces by the Miles engineering skid trailer.

Runway Surface Treatment Evaluation

Data from the present investigation indicate that aircraft stopping distances on dry concrete pavements were usually only slightly less than those obtained on dry asphalt pavements. Slipperiness of runways thus becomes important only when pavements become wet, flooded, or covered with slush, snow, ice, or other contaminants.

Conventional surface treatments (wet conditions).- The runways studied in this investigation are ranked according to slipperiness (wet-dry stopping distance ratio) in table I, first for concrete pavements, and then for asphalt pavements. These data, along with visual observations of the runway surface during test, surface photographs, and the core sample analysis shown in appendix A as well as the engineering data given in appendix C, show that some concrete and asphalt runways although constructed according to conventional surface treatment procedures were slippery when wet. Such slippery surfaces, whether constructed of concrete or asphalt, have several features in common. These features are: lack of surface texture, use of smooth or polished stones in the exposed aggregate of the surface, and relatively poor water drainage. NASA research (ref. 9) indicates that smooth pavements and smooth or polished aggregate stones lack the gritty texture required for aircraft tires to puncture and displace from the tire footprint the thin viscous water film that may create viscous hydroplaning or viscous skidding. The lack of surface texture also makes the tire-pavement combination more susceptible to dynamic hydroplaning when finite water depths cover the pavement. Open-textured pavements, for example, provide many small escape paths for the bulk water

trapped in the tire-ground contact patch to drain outside the footprint and delay dynamic hydroplaning from occurring until greater ground speeds are achieved or deeper water depths are encountered on the pavement. An indication of the effect of surface texture on pavement slipperiness is given by the data shown in figure 26 which shows the variation of aircraft wet-dry stopping distance ratio (table I) with average pavement surface texture depth. As the average texture depth of the pavement increases, the wet-dry stopping distance ratio of the aircraft decreases. The scatter of the data in figure 26 is mainly attributed to the fact that the NASA grease technique used measures gross surface porosity and hence does not distinguish between smooth or polished pavement surfaces having aggregates which are ineffective against viscous hydroplaning, and smooth but gritty surfaces having aggregates which are effective against viscous hydroplaning. The rubber-coated touchdown areas of runways provide another example of the effect of surface texture on pavement slipperiness. These rubber desposits tend to fill the voids and to round the small sharp asperities of a runway surface; thus, the surface texture is made smoother and more susceptible to both viscous and dynamic hydroplaning effects. An ungrooved runway recently tested by the NASA diagonal-braked test vehicle under wet and damp conditions exhibited the following wet-dry stopping distance ratios: rubber-contaminated concrete, 3.46 wet and 3.36 damp; and for clean concrete, 2.42 wet and 1.88 damp. The ratio of 3.36 achieved on this damp rubber-coated concrete runway was larger (more slippery) than that obtained on many of the snow- and ice-covered runways tested in this investigation. (See table II.) It can be seen from table I that the rubber deposits on the grooved runways at John F. Kennedy and Seymour Johnson Airports also increased the pavement slipperiness of these runways. Note that the increase in slipperiness due to rubber deposits is not as severe on the grooved runways investigated as on the ungrooved surfaces.

Conventional surface treatments (flooded or slush-covered conditions).- Under heavy rainfall precipitation rates, conventional runway surface treatments cannot drain the water from the pavement quickly enough to prevent the pavement from flooding and completely covering even open-textured runway surfaces with finite water depths. Under this condition, dynamic hydroplaning reduces aircraft tire-ground braking capability at high speeds as shown in figure 13(c) for the F-4D aircraft. The same situation is true for slush-covered runways as well since slush may act as a viscous fluid.

Conventional surface treatments (snow- and ice-covered conditions).- When snow or ice accumulate on a runway surface to a depth and density that prevents aircraft tires from actually contacting the bare pavement surface, it is obvious that the particular pavement surface treatment underlying the snow or ice cover will have no effect on the aircraft or ground vehicle braking action. The safety hazards that snow and ice create on a runway surface are readily apparent from the magnitude of the aircraft wet-dry stopping distance ratios which are as high as 3.71 (table II). It is noted that these values were

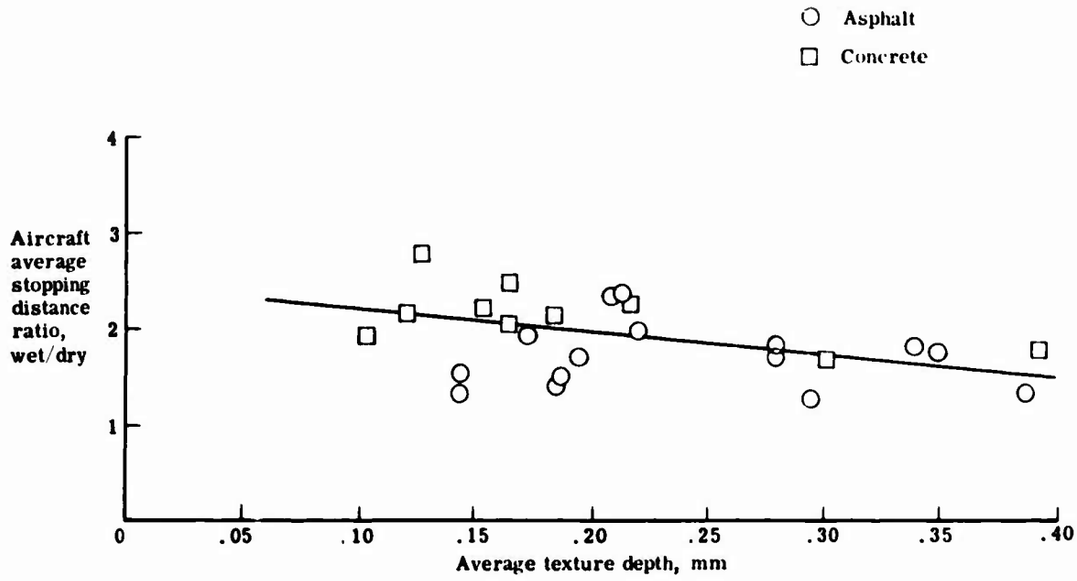


Figure 26.- Variation of aircraft wet-dry stopping distance ratio with runway surface average texture depth (NASA grease test).

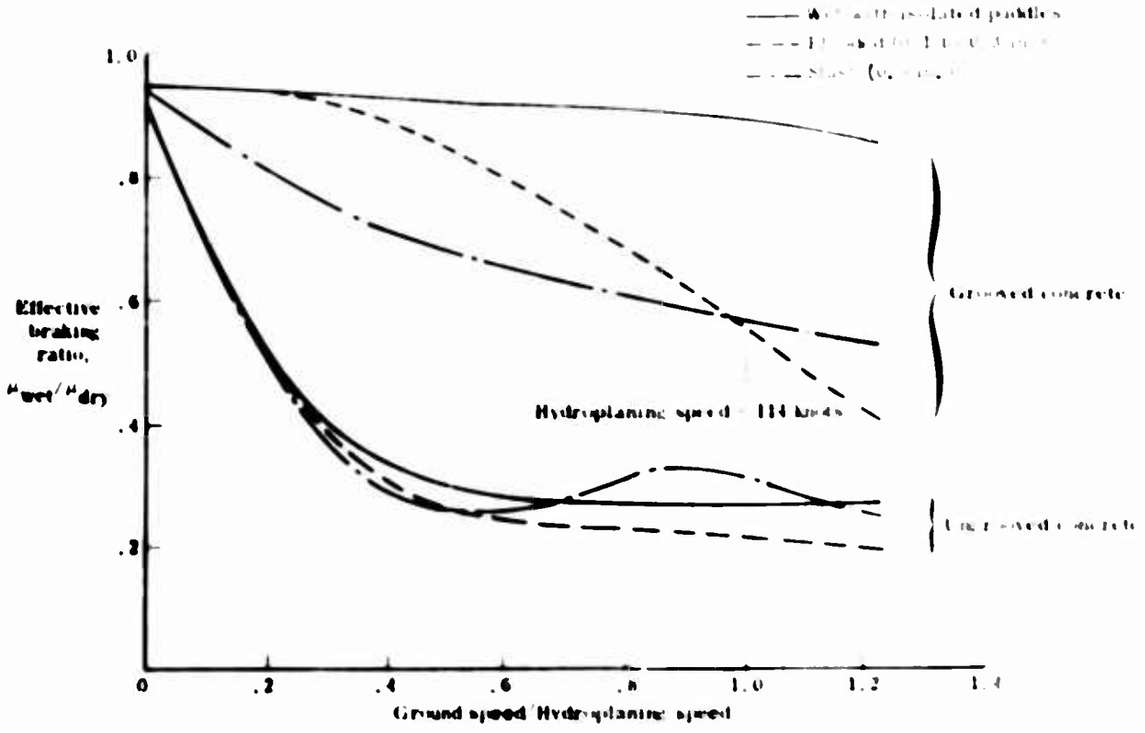
obtained for a relatively cold temperature range from 8° to 27° Fahrenheit where the snow and ice covers are relatively dry. If a sudden thaw were to occur, the warm temperatures would tend to produce first a water film on the packed snow or ice and later a slush condition. A water film on ice (based on wet-ice friction-coefficient data from ref. 9) is estimated to produce wet-dry stopping distance ratios for the aircraft of 8.5 as shown in figure 21. It is important therefore to remove or treat the snow or ice condition on runways and taxiways as quickly as possible.

Unconventional surface treatments (wet or flooded conditions).- Runway surfaces found to provide the best aircraft stopping performance under damp or wet conditions in this investigation were grooved and porous asphalt friction course surfaces. Both grooved and porous surfaces were observed to drain rapidly during times of heavy natural rain so that surface flooding which occurs on conventional surface treatments under such conditions did not normally occur except in isolated small runway low-spot (bird bath) areas.

The aircraft stopping performance on damp or wet grooved pavements was found to be dependent upon the groove arrangement (groove spacing and depth of groove) selected. (See table I.) Best aircraft stopping distance performance was achieved by using 1/4 inch wide by 1/4 inch deep transverse grooves spaced 1 inch apart. These results are in agreement with earlier NASA research on groove configurations described in reference 1. The alternating groove pattern (2 inch by 1/4 inch by 1/4 inch) used at Seymour Johnson Air Force Base and described in appendix C, although shown to be effective (table I) for a damp runway condition, was found to be considerably less effective for a wet runway condition during tests at Wallops Station (see fig. 12) than the 1 inch by 1/4 inch by 1/4 inch groove pattern. As previously described, the limited braking tests at Wallops Station on the C-141A, F-4D, and 990A aircraft indicated that grooved pavements were considerably superior to ungrooved pavements under flooded runway conditions in developing tire-ground braking forces. The porous asphalt surfaces were not tested under flooded runway conditions in this investigation. It is felt, however, that the porous asphalt friction course surface would be effective under flooded conditions because of the internal drainage capacity of this surface configuration.

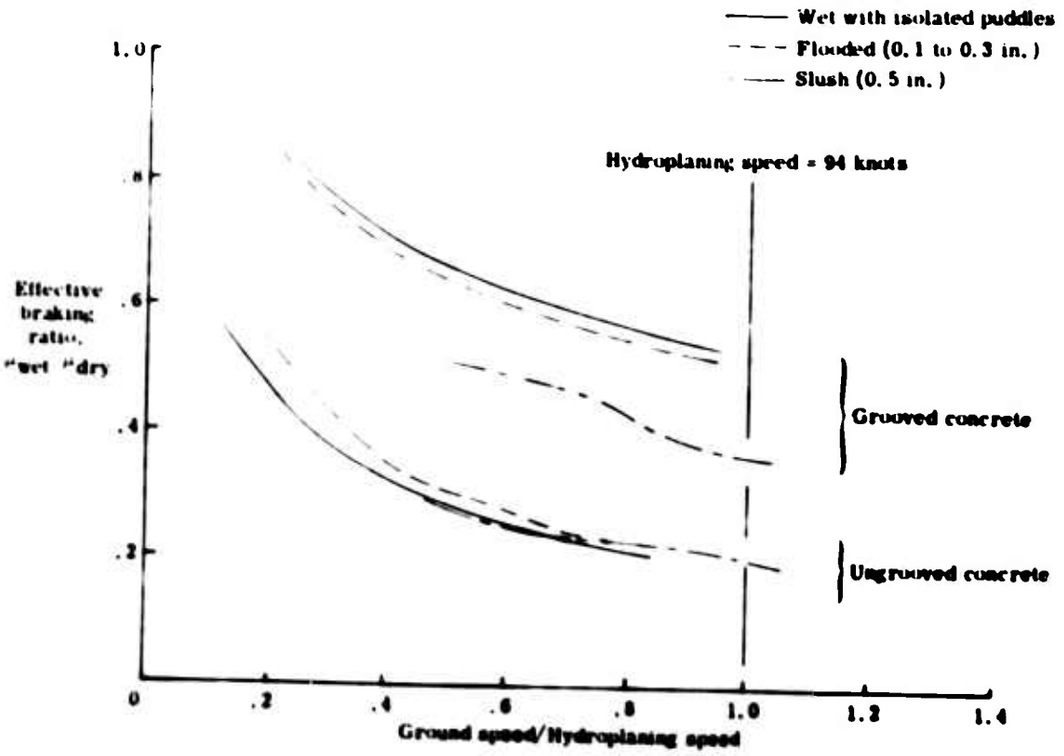
It should be mentioned that synthetic aggregates, such as used in the asphalt surface at Meigs Airport, may be a solution for runway construction areas in which the local aggregate is smooth and possesses low friction qualities. Such aggregates could be used in porous friction course or open-textured asphalt surface treatments.

Unconventional surface treatments (slush, snow, or ice conditions).- The limited braking tests at Wallops Station show that for the C-141A and 990A aircraft, grooved pavements are superior to ungrooved pavements when under a slush cover. (See fig. 27.) The porous asphalt friction course was not studied under a slush condition in this



(a) 990A aircraft; five-groove tire; inflation pressure, 160 lb/in^2.

Figure 27.- Effect of runway grooves on aircraft braking performance.



(b) C-141A aircraft; five-groove tire; inflation pressure, 110 lb/in^2.

Figure 27.- Concluded.

investigation. The fact that grooved and porous pavement treatments drain quickly also means that they dry quickly, and as a result, ice formation on the runway during cold temperatures should be alleviated. It has been noted (ref. 1) that when thin ice forms on grooved runways at, near, or slightly below freezing ambient air temperatures, tire passage over the ice-covered grooved pavement shatters the ice in the tire-ground contact zone and friction is improved. Tire passage on an adjacent ungrooved pavement under the same thin-ice temperature conditions did not disturb the ice bond to the pavement and friction was very low. The same type of improvement in aircraft and ground vehicle performance furnished by grooved pavements under this ice condition has also been observed on the porous asphalt friction course surface at Marham RAFB. Unfortunately, snow conditions were not available for test on unconventional surfaces.

Unconventional surface treatments (other factors).- As of July 1970, 23 concrete and asphalt runways have been grooved worldwide. (See table III.) The experience thus far (ref. 1) shows that pavement deterioration from grooving, especially on concrete surfaces, has not been a significant problem. Grooved plant mix asphalt runways with dense aggregate such as those at Farnborough, Washington National, and Kansas City have had no significant pavement deterioration problems. Asphalt taxiway grooves have failed and collapsed when the grooving treatment was applied to thin asphalt slurry-seal runway coatings. Groove-collapsing-type failures also have occurred on the runway at Tempelhof. (See fig. A1(bb).) In this instance, the grooving treatment was installed on the surface of a plant-mix asphalt runway that had a 1/8-inch German antiskid coating applied to the original surface. The surface photographs in figure A1(bb) show that the 1/8-inch antiskid coating has slipped with respect to the original surface and has flowed into the runway grooves. The grooves in the original plant-mix asphalt underlying the surface coating have maintained integrity.

Reference 1 reports that the most significant new aircraft operational problem that can be attributed to pavement grooving is the chevron cutting of aircraft tires at the moment of touchdown during landing. NASA research indicates that chevron cutting occurs only on the larger size aircraft tires where large wheel moment of inertias produce high wheel spin-up drag loads on aircraft tire treads at touchdown. Preliminary results of a study being conducted at the NASA landing loads track on a large 49 × 17 aircraft tire (see fig. 28) indicate that damages from chevron cutting are functions of touchdown speed, inflation pressure, and tread rubber compound. Damage index in figure 28 is simply the product of the chevron cut damaged area of the tire tread and the deepest chevron cut. The index furnishes an indication of the volume of tire-tread rubber affected. Tire I in figure 28 used a tread rubber compound in wide use before pavement grooving was initiated on runways. Tire II in figure 28 used a new tread rubber compound expressly made to alleviate chevron cutting. It is apparent from these results that tread rubber compounding is a promising way to alleviate this aircraft operational problem.

TABLE III.- GROOVED RUNWAYS - July 1970

All runways have transverse groove patterns with rectangular cross section unless otherwise noted

Type	Location	Material	Year grooved	Groove pattern		
				Pitch, in.	Width, in.	Depth, in.
Military (Continental)	Beale AFB, Calif.	Concrete	1968	1	1/4	1/4
	Seymour-Johnson AFB, N.C.	Concrete and asphalt	1968	*2	1/4	1/4
	Offutt AFB, Nebr.	Concrete	1969	1 1/4	1/4	1/4
Military (Overseas)	Ubon, Thailand	Concrete	1966	*2	1/4	1/4
	Udorn, Thailand	Concrete	1966	*2	1/4	1/4
	Shemya, Alaska	Asphalt	1970	1 1/4	1/4	1/4
	Kadena, Okinawa	Concrete and asphalt	1970	1 1/4	1/4	1/4
	Bien Hoa AB, S. Vietnam	Concrete	1967	*2	1/4	1/4
Civil	Washington National	Asphalt	1967	1	1/8	1/8
	Kansas City Municipal Airport	Concrete and asphalt	1967	1	1/8	1/4
	John F. Kennedy Airport, N.Y.C.	Concrete	1967	**1 3/8	3/8 top 3/16 bottom	1/8
	Kanawha Airport, Charleston, W. Va.	Concrete and asphalt	1968 and 1969	1 1/4	1/4	1/4
	Midway Airport, Chicago, Ill.	Concrete	1968	1 1/4	1/4	1/4
	Atlanta, Ga.	Concrete	1969	**1 1/4	3/8 top 1/8 bottom	1/4
	Nashville, Tenn.	Concrete and asphalt	1969	1 1/4	1/4	1/4
	Dallas, Texas	Concrete	1969	1 1/4	1/4	1/4
	O'Hare Airport Chicago, Ill.	Asphalt	1969	1 1/4	1/4	1/4
	Harry S. Truman Airport, Virgin Islands	Concrete and asphalt	1970	1 1/4	1/4	1/4
Foreign	Farnborough, England	Asphalt	1961	1	1/8	1/8
	Birmingham, England	Asphalt	1967	1	1/8	1/8
	Manchester, England	Asphalt	1961 and 1965	1	1/8	1/8
	Temperlhof, Germany	Asphalt	1968	1 1/2	3/8	3/8
	Wellington, New Zealand	Asphalt	1969 and 1970	1	1/8	1/8

*Groove 2 feet, skip 2 feet.
**V-shape groove cross section.

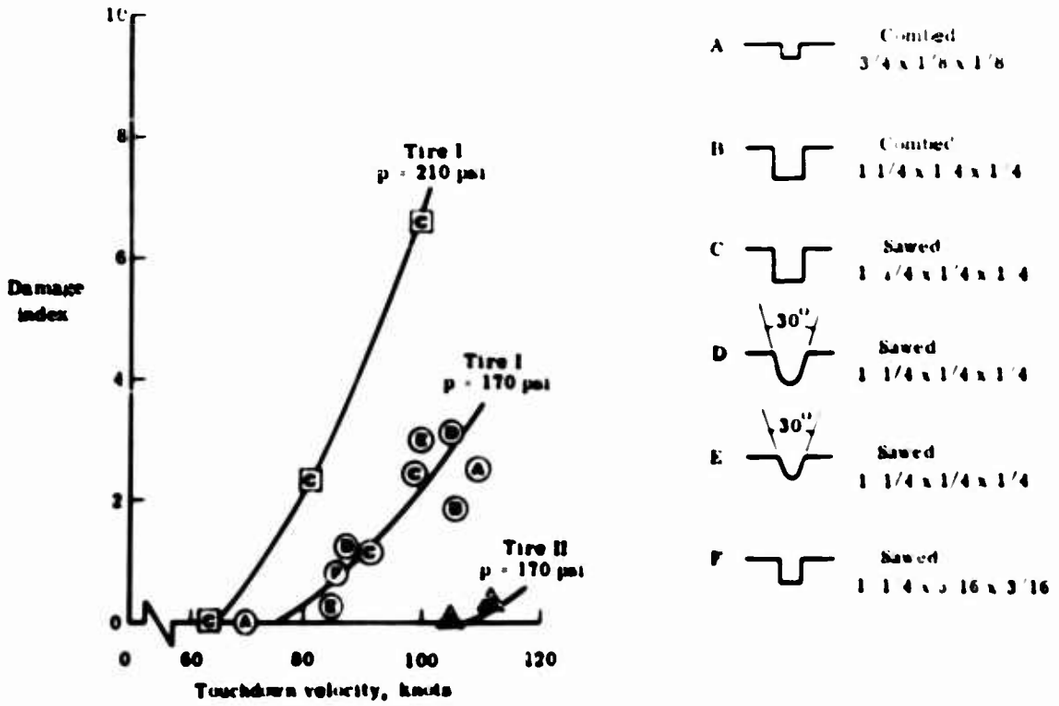


Figure 28.- Tire chevron cutting on grooved surfaces. 49 × 17 tire; vertical velocity, 2.5 ft/sec. Measurements are in inches for runway surfaces unless otherwise noted.

Based on operational experiences, the USAF has noted that Offutt Air Force Base and Beale Air Force Base have experienced chevron cutting on the larger tire sizes due to runway grooves. The groove patterns at these bases are 1/4 inch by 1/4 inch on $1\frac{1}{4}$ inch centers and 1/4 inch by 1/4 inch on 1 inch centers. Limited testing during the Combat Traction tests consisted of two landings on the grooved runway at Wallops Station which resulted in minor tire cuts. More tests were scheduled at Beale Air Force Base but could not be accomplished because the airplane was down for maintenance. From the reports received, the severity of cutting is a function of tread rubber composition, tire size, and the number of consecutive touch-and-go landings made. The cuts are small and shallow and are usually worn off when full stop landings are accomplished. The most severe cuts reported are the result of several consecutive touch-and-go landings.

A problem noted for the porous asphalt friction course surfaces studied in this investigation was from fuel spillage on the runway that occurred during a helicopter mishap. The fuel dissolved the asphaltic binder of the friction course and loosened the aggregate. The section of the runway surface involved in the fuel spillage had to be repaved.

It may be noted that two techniques are available for providing standard low levels of runway slipperiness. Runway grooving has been shown to develop similar results for different runways. For example, the concrete runway at Offutt (runway 15, table I) and the Chicago Midway (runway 14, table I) were grooved to similar patterns and gave remarkably similar results. Also a porous asphalt friction course has been shown to provide similar results for different runways (runways 36 and 38, table I).

CONCLUSIONS AND RECOMMENDATIONS

Full-stop brake tests were made by the C-141A aircraft, the runway condition reading (RCR) vehicle, and the diagonal-braked test vehicle on civil and military runways in the United States and Europe under dry, artificially wet, natural rain, ice, and snow conditions. Included in the European program were tests conducted jointly with the British Ministry of Aviation Supply on Royal Air Force and Royal Navy Bases using a Mu-meter and the Miles engineering skid trailer. Limited brake tests were also conducted on the landing research runway at NASA Wallops Station, Virginia, with the C-141A aircraft. An analysis of the test results indicates the following:

1. Runway condition reading (RCR) now in use by the U.S. Air Force is not an adequate method for predicting aircraft stopping distance on a wet runway, but it can be used to conservatively predict stopping distance on ice- and snow-covered runways.

2. A diagonal-braked vehicle can be used to predict aircraft stopping distance and crosswind limitations for wet, ice-, and snow-covered runways and can be used to measure runway slipperiness.

3. Grooved pavements and porous asphalt surfaces were the most effective surface treatments investigated in alleviating surface flooding and wet runway slipperiness.

4. Aircraft stopping distance generally increases with increasing water depth on the runway.

On the basis of these test results, the following recommendations are made:

1. Engineer, design, and test a diagonal-braked vehicle which will be suitable for Air Force operations use.

2. Continue research and development of runway groove designs and spacing and of tire-tread compounds to alleviate tire cutting and excessive tire wear.

3. Develop a rainfall-precipitation-rate—water-depth measuring system for runways to provide real-time runway condition information and reduce the number of operational measurements needed with the diagonal-braked test vehicle.

4. Gather data (tire wear, pilot comments, ambient temperature variations, rainfall and rainfall rate, snowfall, effect of jet-exhaust impingement and resistance of the asphaltic binders to aircraft fuels) on the existing Air Force porous runways and continue research on porous runways.

5. Test additional aircraft with various landing-gear configurations, tire sizes, and tire groove patterns on full-length dry, wet, flooded, ice-, and snow-covered runways to verify correlation with a diagonal-braked test vehicle.

6. With the replacement of RCR vehicles by diagonal-braked test vehicles, change RCR to stopping distance factor (SDF) by issuance of appropriate supplements to the flight handbooks of military and civil aircraft affected.

7. Measure the slipperiness of each Air Force runway with an instrumented diagonal-braked vehicle to assemble a priority list of runways in need of surface treatment.

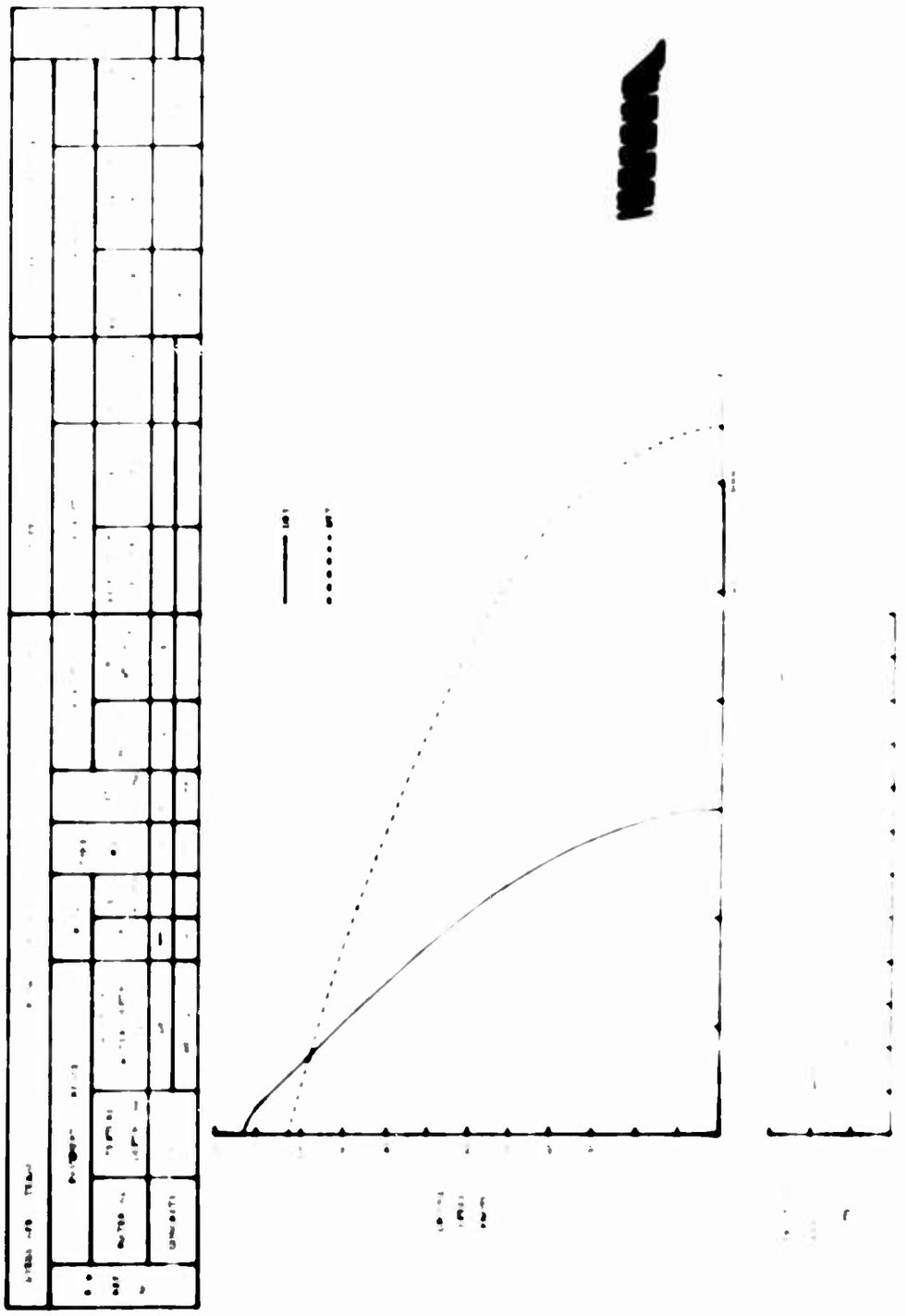
Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., November 7, 1970.

APPENDIX A

COMPILATION OF TEST DATA

The data compiled and tabulated for each test runway are presented in this appendix in the order of aircraft wet-dry stopping distance ratios as listed in tables I and II. Figure A1 shows the data compiled on each runway. This compilation includes the following data: a photograph and description of the pavement surface condition; texture depth measurements; wind direction and velocity; ambient temperature; aircraft heading and gross weight; aircraft and diagonal-braked test vehicle stopping distances and ratios; RCR data; and curves showing the variation of aircraft stopping distance and braking friction coefficient with ground speed. These curves, based on the recorded aircraft deceleration levels, were obtained from the computational procedure described in appendix B. If available, core sample analysis data and photographs are also included for the test runways. Test data are not presented for runways 17 (Mildenhall Air Force Base) and 39 (Meigs Airport) as the aircraft was not tested. Data for runway 49 are included with those of runway 41 (Malmstrom Air Force Base). Note that for runway 15, data are included for two different aircraft gross weight conditions.

APPENDIX A



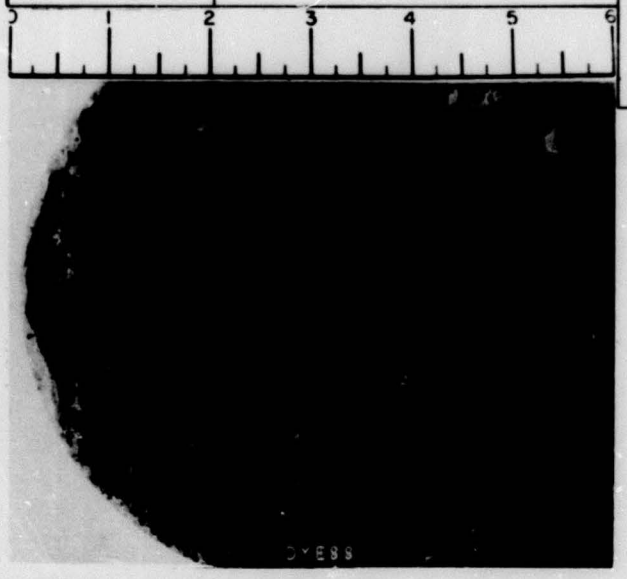
(a) Runway 1; Dyess Air Force Base.

Figure A1.- Runway and vehicle data for runways tested.

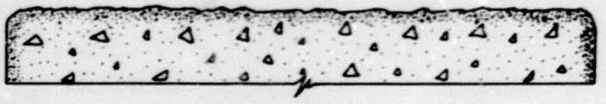
DYESS AFB, TEXAS RUNWAY: 16/34 DATE 9-24 & 25-69

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATION
Portland Cement Concrete Burlap-Drag Finish	Poor surface drainage. Exposed particles of fine sand. Rubber coatings. Fine grained texture.	The surface texture characteristics of the sample of portland cement concrete from Dyess AFB are described as follows: (1) A burlap-drag finish on a fine grained sand-mortar surface. (2) Very little surface texture resulting from exposed particles of sand. Fine texture with some rubber coating. (3) The surface configurations resulting from the burlap-drag finish offer very little surface drainage from the wheel track. The structural characteristics reflected at a depth of 1-1/2 in. below the surface are as follows: (1) The coarse aggregate skeleton consists of a mixture of rounded particles of quartz gravel and fragments of calcareous material. Maximum particle diameter is about 2-1/2 in. (2) The dense graded mix offers no subsurface drainage.	Medium-Poor



CORE SAMPLE SURFACE



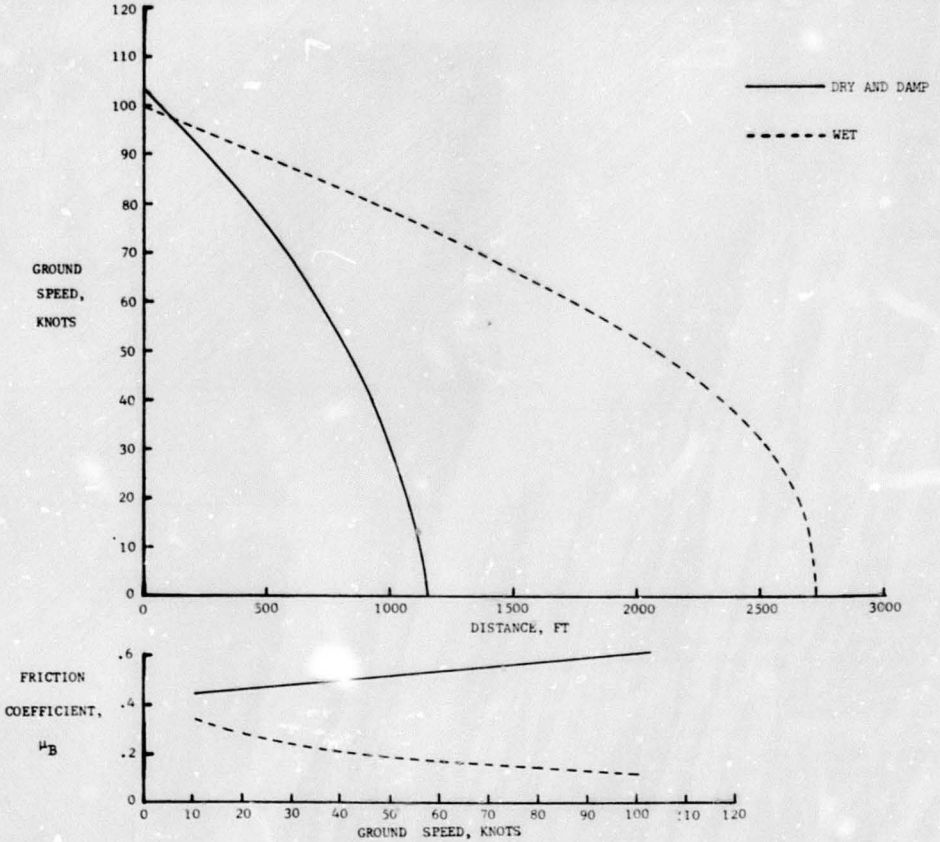
CORE SAMPLE SURFACE PROFILE

(a) Concluded.

Figure A1.- Continued.

ENGLAND AFB, LOUISIANA				RUNWAY 14/32				DATE 10-13-69		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
2	CONCRETE	0.166	DRY AND DAMP	290	6	63	29.98	320	200,400	978	1080	277	2.46*	2.49*	2.16	22
			WET (.05)	310	5	63	29.99	320	193,800	2705	2740	598				15

*Based on S_{DRY} = 1100 ft





TEST SURFACE

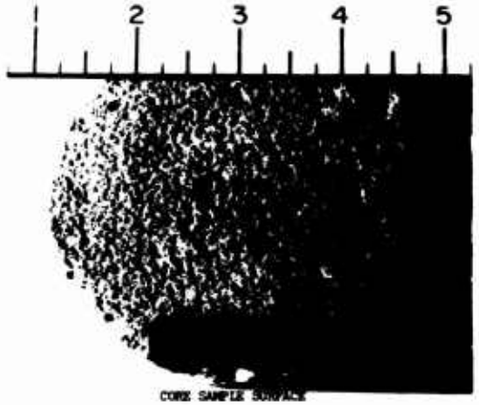
(b) Runway 2; England Air Force Base.

Figure A1. - Continued.

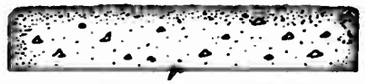
ENGLAND AFB, LOUISIANA RUNWAY 14/32 DATE 10-13-69

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATION
Portland Cement Concrete	Poor surface drainage. Exposed particles of fine sand and some cavitation resulting from dislodgement of particles. Fine grained texture.	The surface texture characteristic of the portland cement concrete from England AFB are described as follows: (1) The fine grained surface texture is defined by exposed particles of sand and mortar cavitation resulting from particle dislodgement. (2) The surface texture affords little surface drainage. The structure characteristics reflected at a depth of 1-1/2 in. below the surface are as follows: (1) The coarse aggregate skeleton consists of rounded particles of quartz gravel well graded between 1/4 and 1 in. in diameter. (2) The dense particles and matrix offer no subsurface drainage.	Medium-Poor



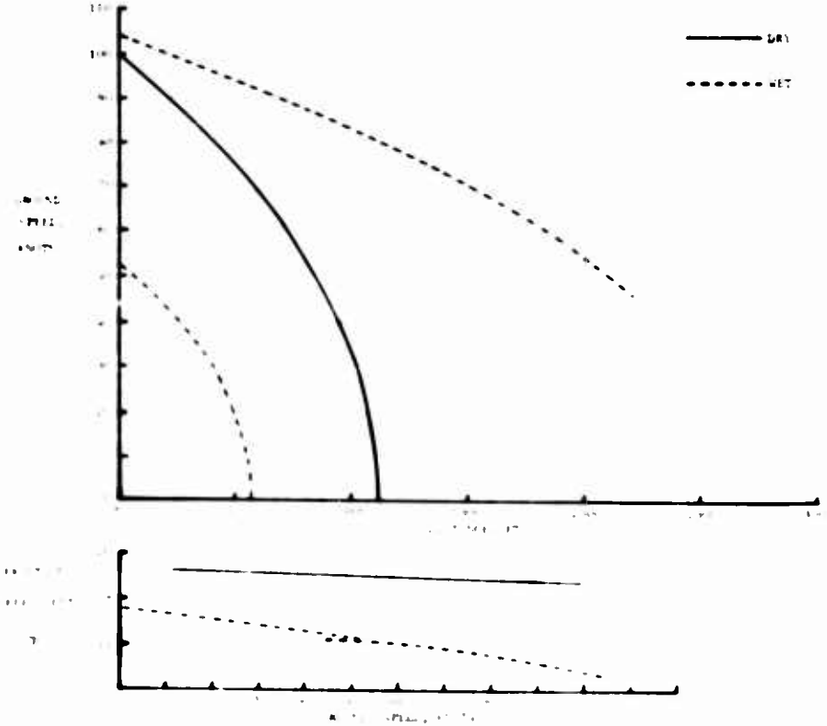
CORE SAMPLE SURFACE

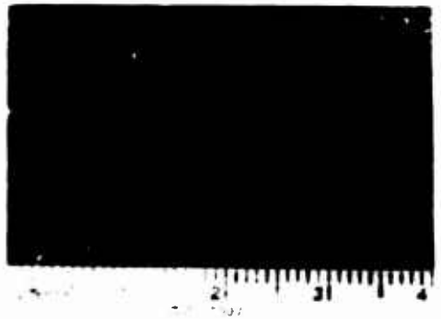

CORE SAMPLE SURFACE PROFILE

(b) Concluded.

Figure A1.- Continued.

MARHAM RAFB, ENGLAND				RUNWAY 2/20				DATE 7-22-69		DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REP. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, in.	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
3	CONCRETE	0.217	DRY	230	5	61	30.04	200	149,400	1030	1110	363	2.29	2.50	1.93	23
			WET (.04) / WET (.05)	240 / 220	7 / 5	61 / 62	30.04 / 30.05	200	148,400 / 148,400	2360	2660	702				23

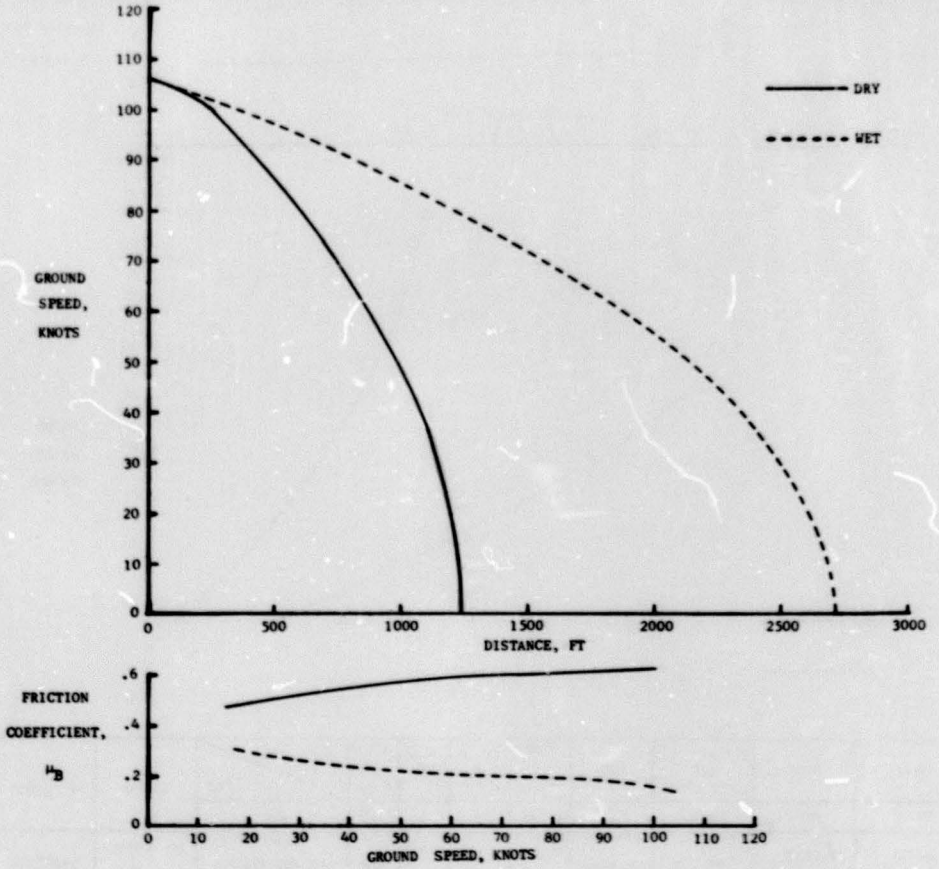




(c) Runway 3; Marham Royal Air Force Base.

Figure A1.- Continued.

OFFUTT AFB, NEBRASKA				RUNWAY 12/30				DATE 9-10-69		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
4	UNGROOVED CONCRETE	0.154	DRY	050	1	54	30.18	300	194,300	974	1000	280	2.28	2.35	2.15	26
			WET (.04)	085	1	56	30.18	300	189,500	2220	2360	601				21





TEST SURFACE

(d) Runway 4; Offutt Air Force Base.

Figure A1.- Continued.

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Portland cement concrete	Medium surface drainage. Exposed particles of rounded aggregate. Dull non-glossed surface texture	The surface texture characteristics of the sample of portland cement concrete from Offutt AFB are described as follows (1) The medium grained surface texture is defined by an exposed particles of fine gravel (approximately 1/8 to 1/4 in.). The exposed particles are, in general, rounded and projected. (2) The interparticle depressions afford a limited amount of surface drainage The structural characteristics reflected at a depth of 1-1/2 in. below the surface are as follows (1) The aggregate skeleton consists of a mixture of fine gravel and fragments of calcareous rock (approximately 15 percent calcareous) (2) The dense graded pavement offers no subsurface drainage even though there is evidence of air voids (bubbles) in the matrix	Medium Macro

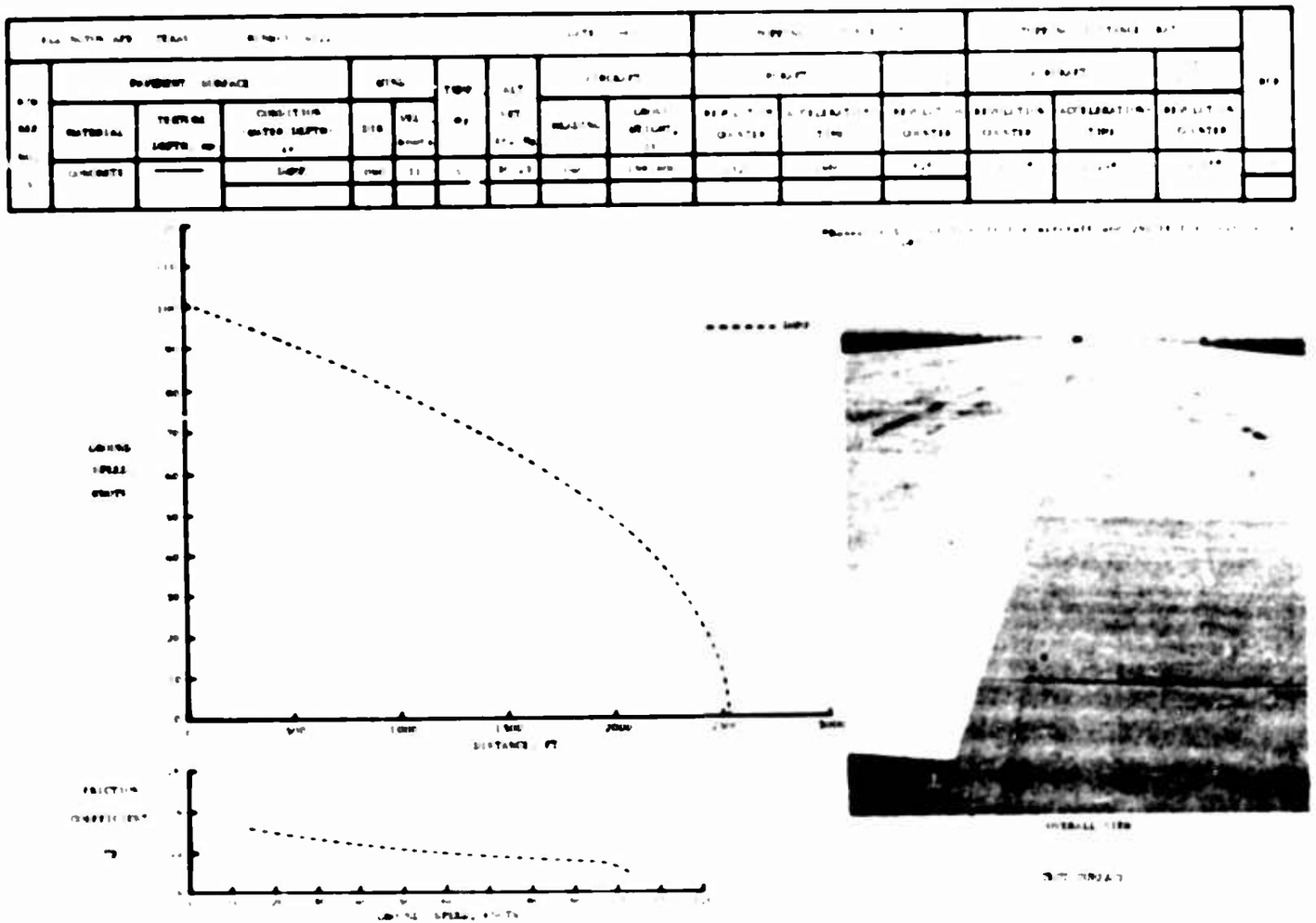




[illegible]

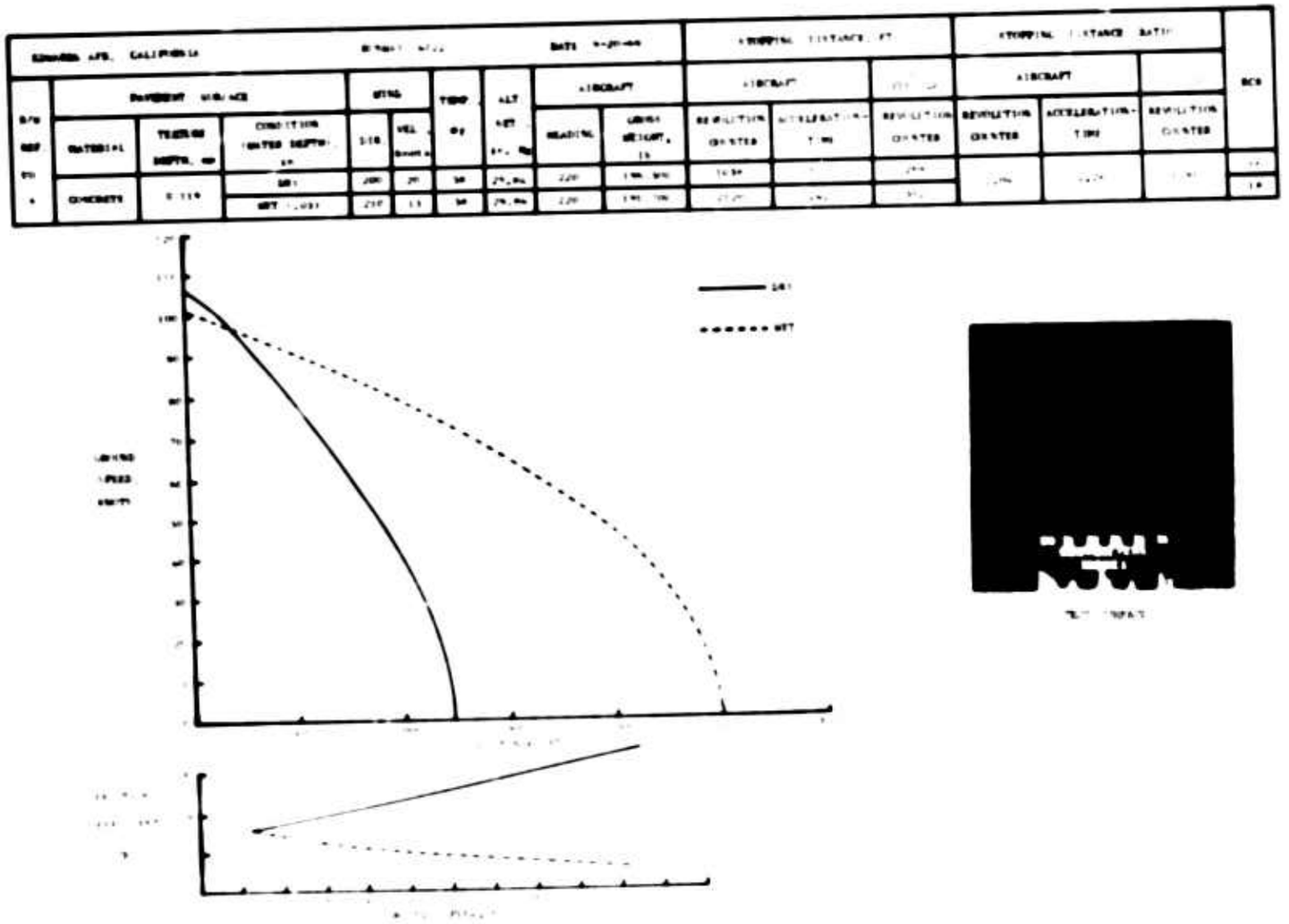
(d) Concluded.

Figure A1.- Continued.



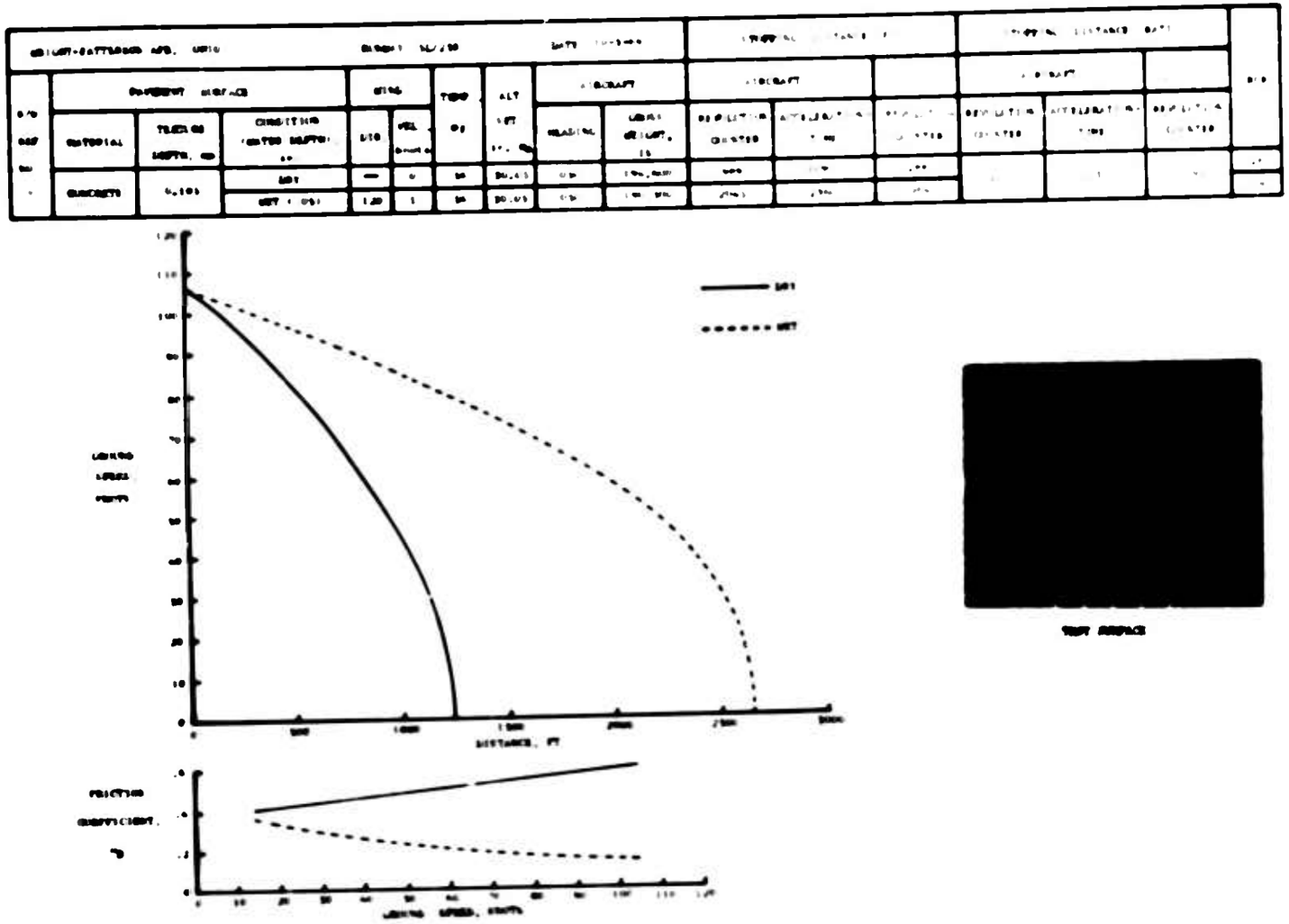
(e) Runway 5; Ellington Air Force Base.

Figure A1.- Continued.



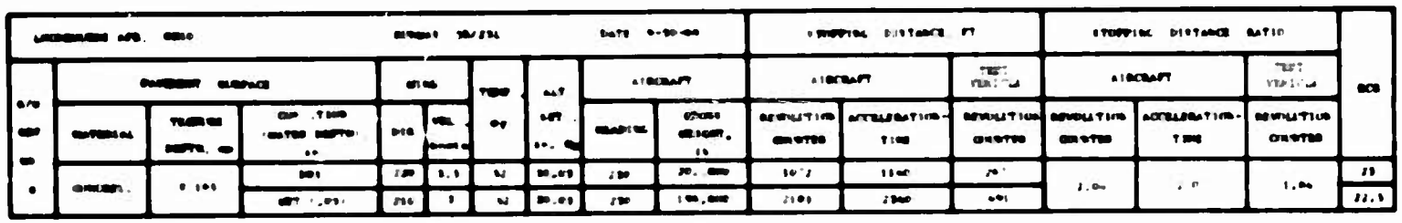
(f) Runway 6; Edwards Air Force Base.

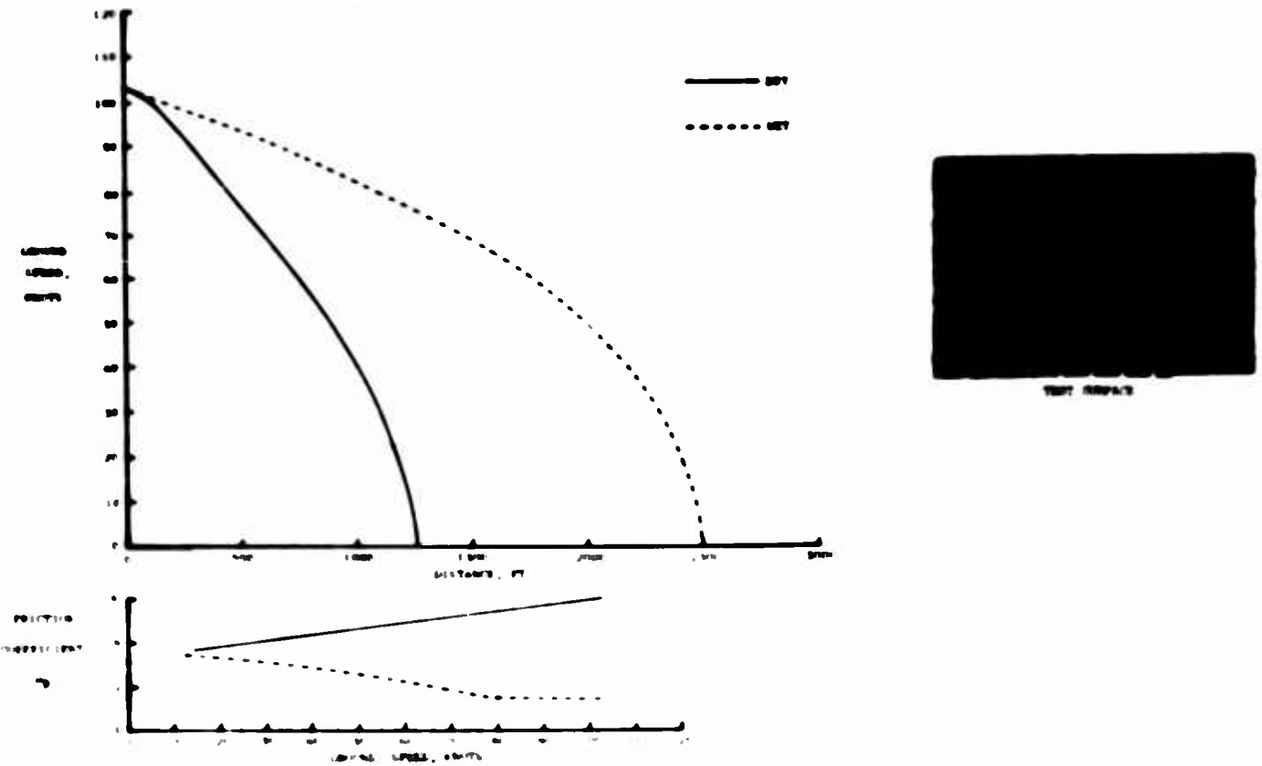
Figure A1.- Continued.



(g) Runway 7; Wright-Patterson Air Force Base.

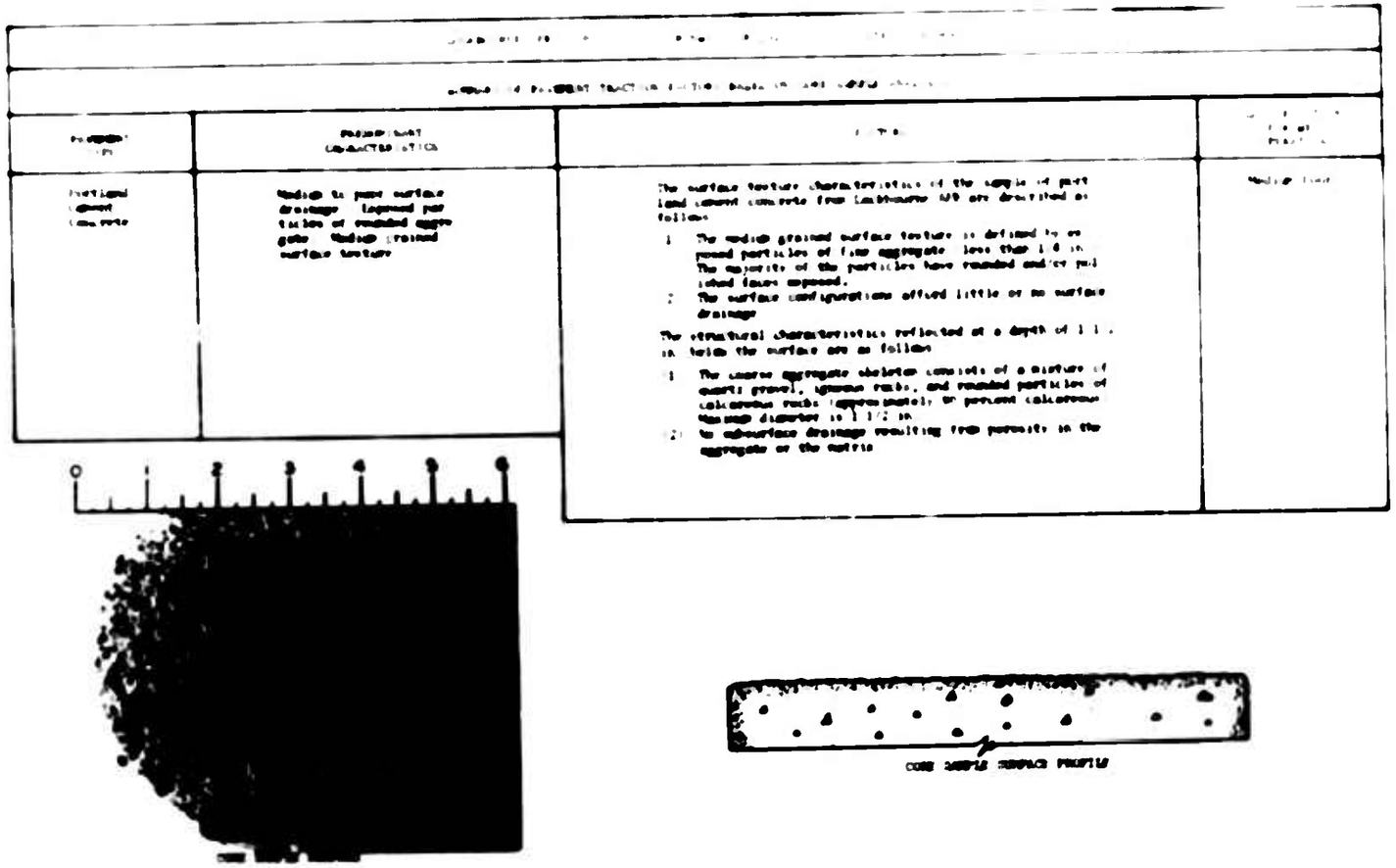
Figure A1.- Continued.





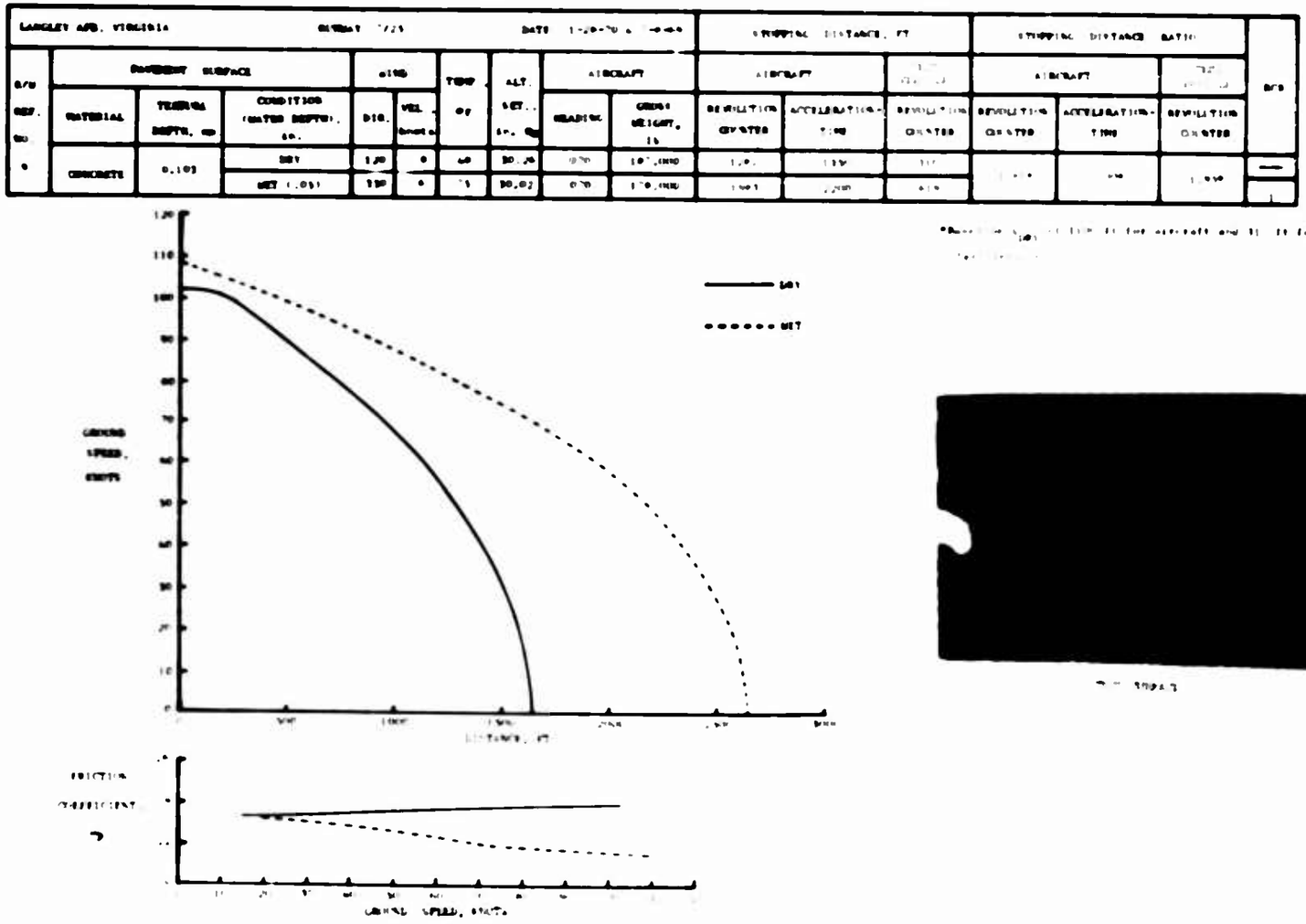
(h) Runway 8; Lockbourne Air Force Base.

Figure A1.- Continued.



(b) Concluded.

Figure A1.- Continued.



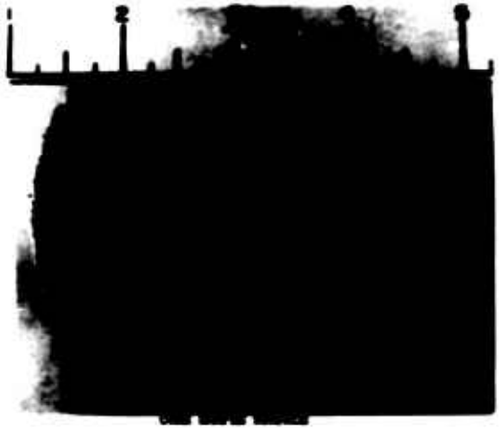
(i) Runway 9; Langley Air Force Base.

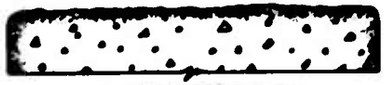
Figure A1.- Continued.

LANGLEY AFB, VIRGINIA

SUMMARY OF PAVEMENT TEXTURE FACTOR BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	
Portland Cement Concrete	Medium surface drainage. Exposed particles of sharp and rounded aggregate. Medium grained texture.	The surface texture characteristics of the portland cement concrete from Langley AFB are described as follows: (1) The medium grained surface texture is defined by exposed particles of fine aggregate (less than 1.0 in). The exposed particles reflect rounded as well as fractured faces. (2) The interparticle depressions provide some surface drainage. The surface characteristics reflected at a depth of . 1/2 in. below the surface are as follows: (1) The coarse aggregate skeleton consists of quartz gravel and fragments of igneous rock. The maximum diameter is 2 1/2 in. (2) No subsurface drainage is reflected in the dense particles or the matrix	Medium



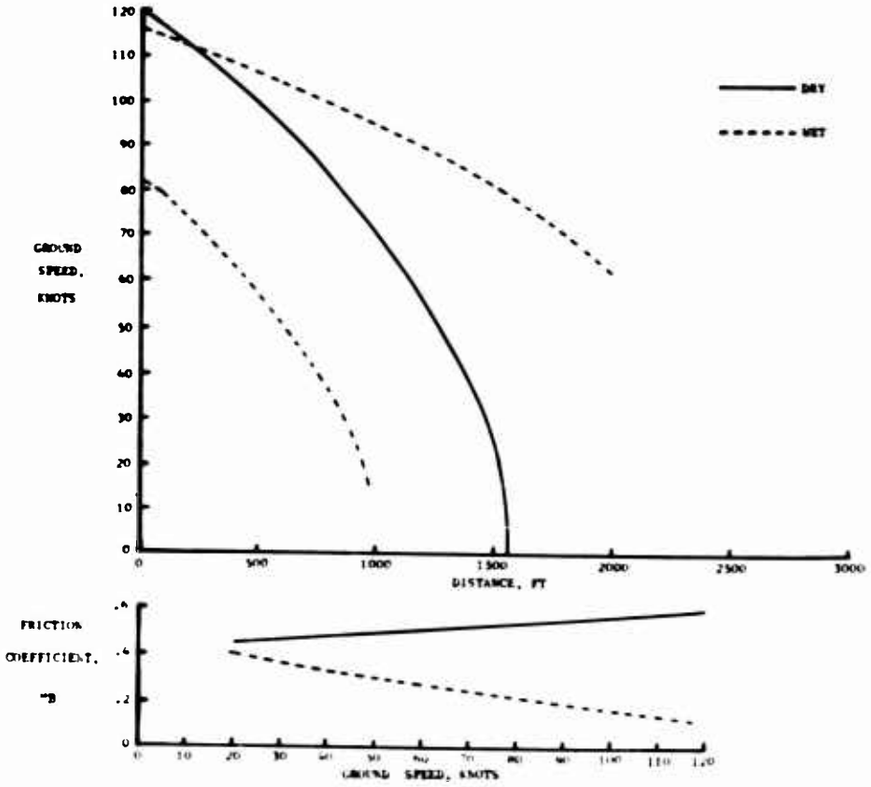


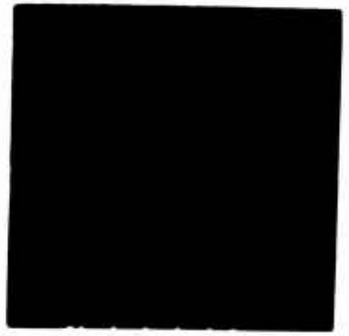
CORE SAMPLE SURFACE PROFILE

(i) Concluded.

Figure A1.- Continued.

YEOVILTON NAB, ENGLAND				RUNWAY 9/27			DATE 7-19-66			STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REP. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, cm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
10	WIRE COMBED CONCRETE	0.305	DRY	240	4	64	30.16	090	180,000	1023	1040	312	1.87	1.70	1.63	22
			WET (.02) / DAMP	230 / 230	5 / 4	64 / 64	30.16 / 30.16	090 / 270	175,900 / 172,400	1914	1800	513				23



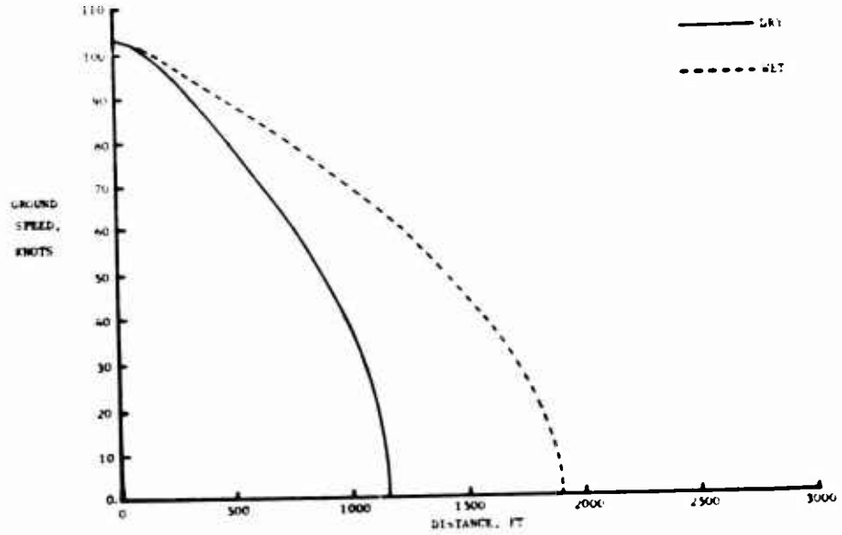


TEST SURFACE

(j) Runway 10; Yeovilton Royal Naval Base.

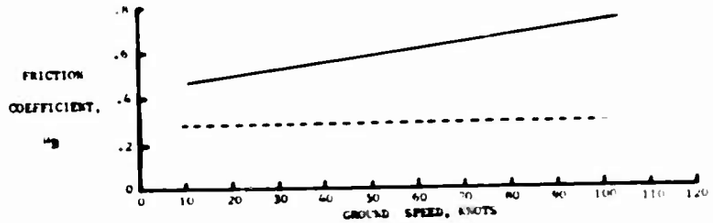
Figure A1.- Continued.

YEOVILTON RNB, ENGLAND				RUNWAY 07/25					DATE [illegible]							
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		TAKEOFF			LANDING			
	MATERIAL	TEXTURE DEPTH, in.	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	RUN DISTANCE OVER 50 FEET	AIRBORNE DISTANCE	RUN DISTANCE OVER 50 FEET	RUN DISTANCE OVER 50 FEET	AIRBORNE DISTANCE	RUN DISTANCE OVER 50 FEET	
11	SCORED CONCRETE	0.394	DRY	240	5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
			WET (.04")	220	6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	





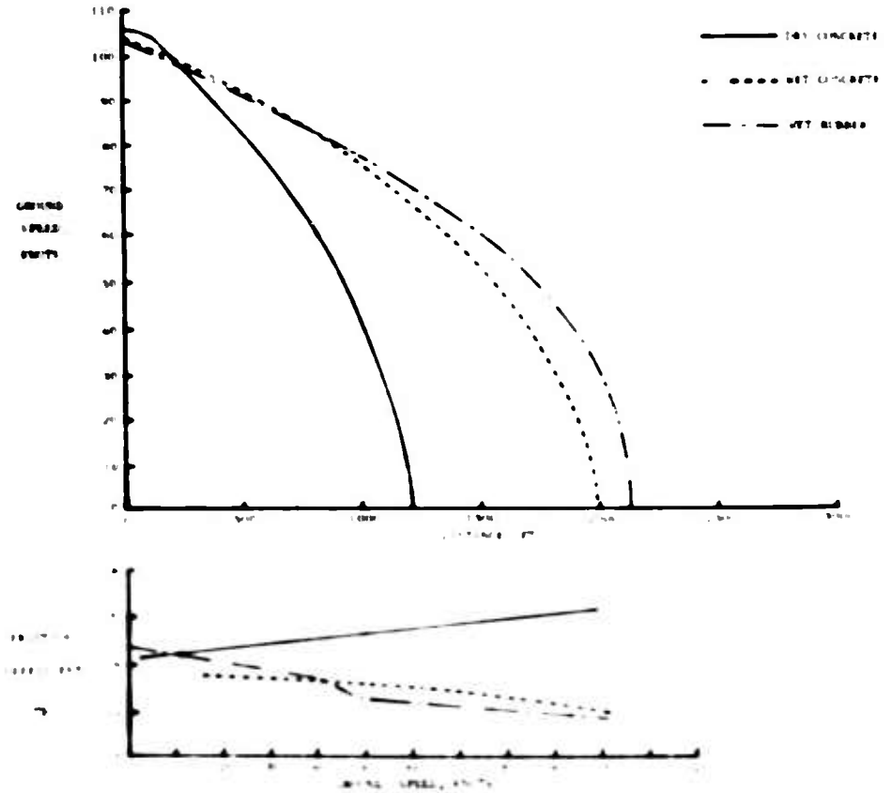
TEST SURFACE

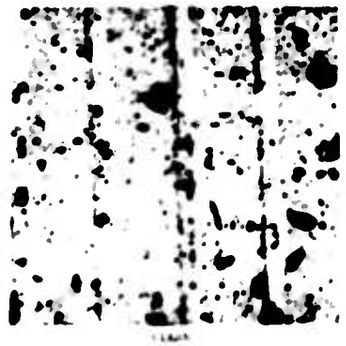


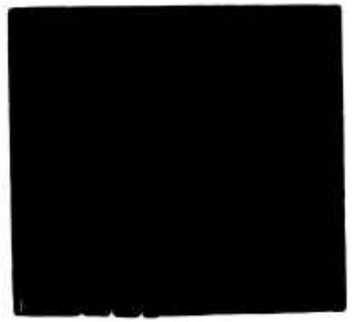
(k) Runway 11; Yeovilton Royal Naval Base.

Figure A1.- Continued.

JOHN F. KENNEDY AIRPORT, NEW YORK														
R/W END ID	PAVEMENT SURFACE			WIND		TEMP	ALT. SET.	AIRCRAFT		LANDING DISTANCE - FT				ACN
										AIRCRAFT				
	MATERIAL	TEXTURE DEPTH, IN	CONDITION (WATER DEPTH), IN	DIR.	VEL. KNOTS	°F	IN. HG	HEADING	GROSS WEIGHT, 1000 LB	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
12	GROOVED CONCRETE	—	DRY	200	9	70	30.09	120	190.000	—	10.0	30	—	—		—
			WET (.01)	200	9	70	30.09	120	190.000	10.0	10.0	33				—
	RUBBER		WET (.04)	190	9	71	30.10	120	190.000	10.0	10.0	33	—	—		—

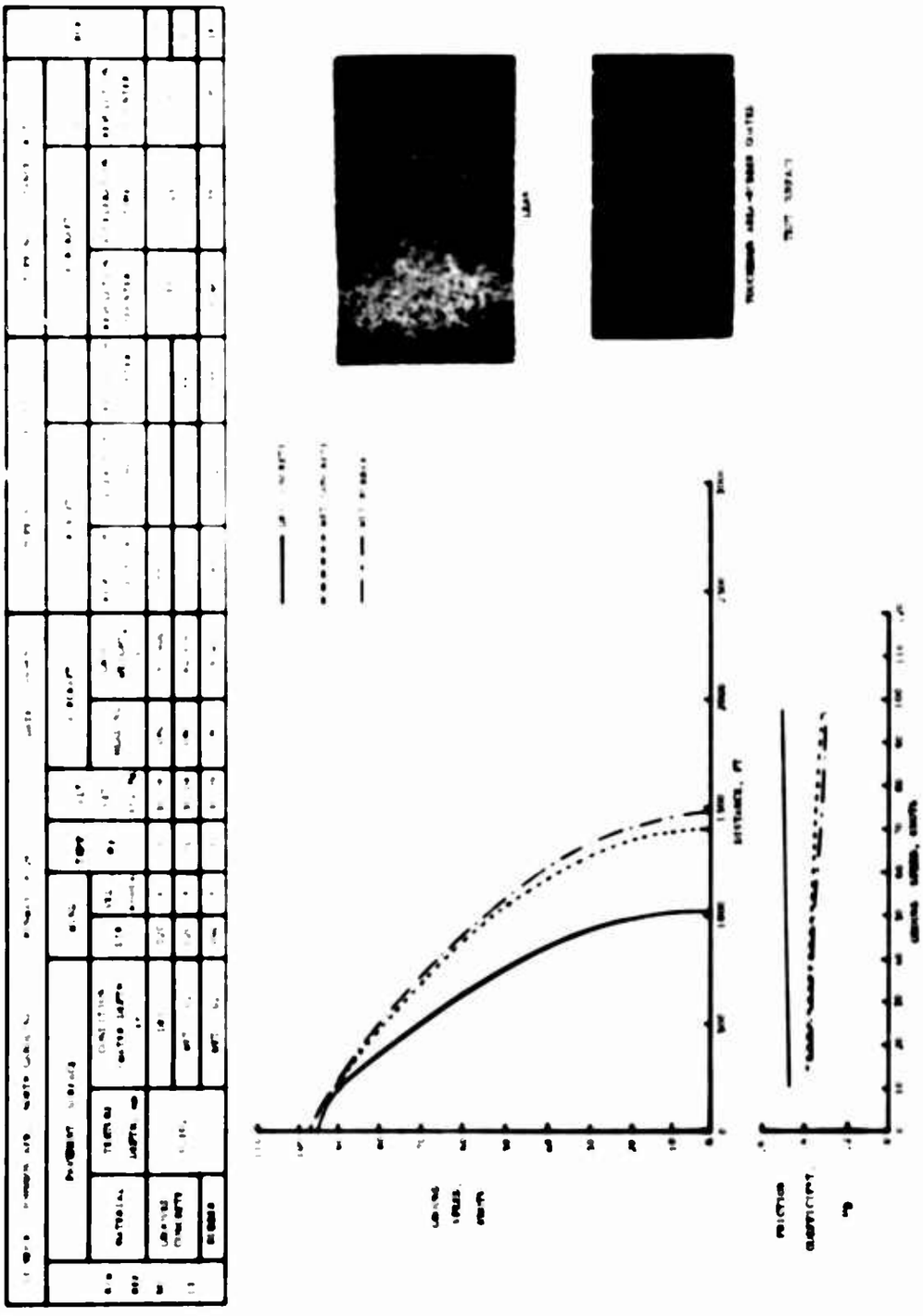






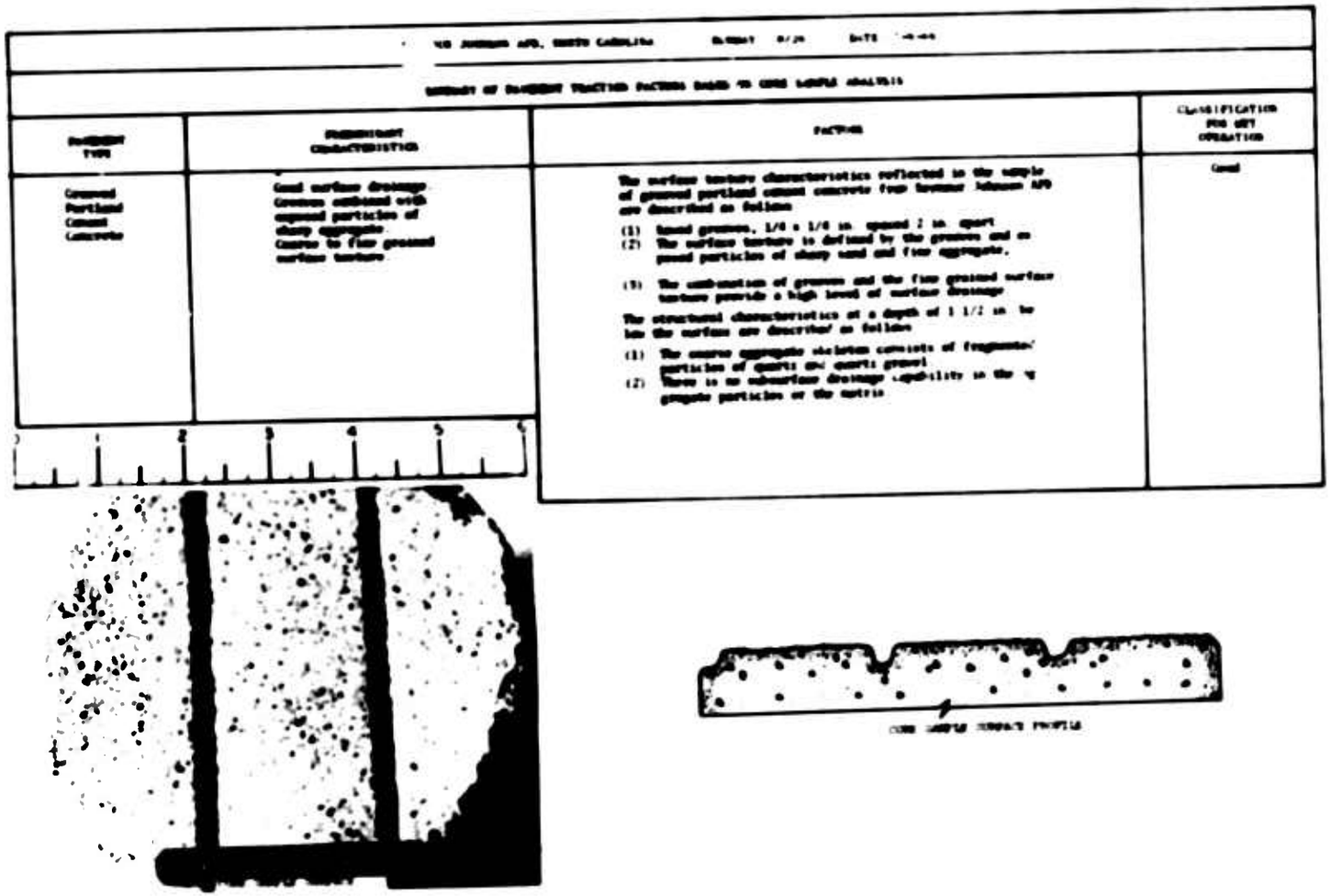
(l) Runway 12; John F. Kennedy Airport.

Figure A1.- Continued.



(m) Runway 13; Seymour Johnson Air Force Base.

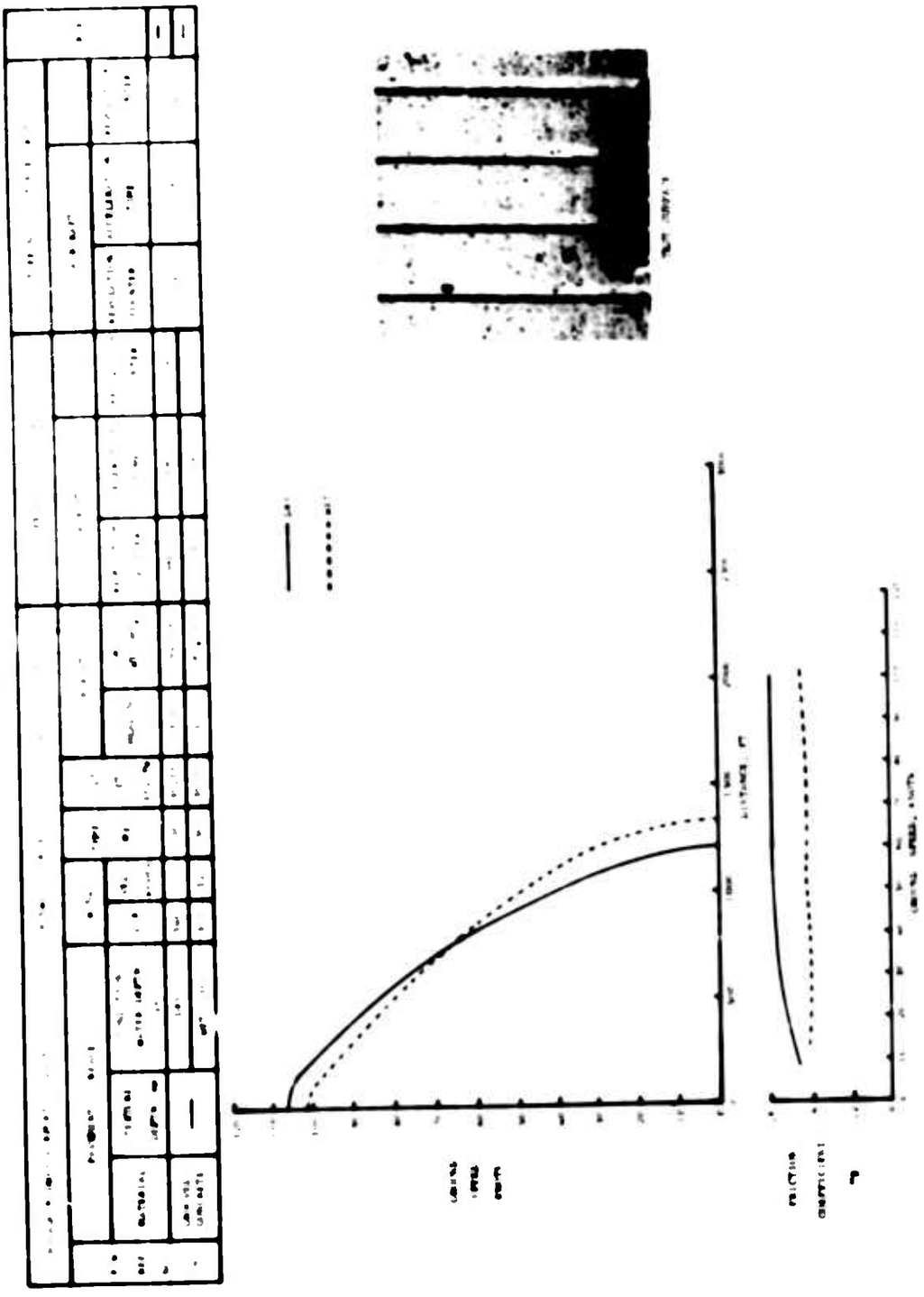
Figure A1.- Continued.



PAVEMENT TYPE	PAVEMENT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR SKET OPERATION
Grooved Portland Cement Concrete	Good surface drainage Grooves combined with exposed particles of sharp aggregate Coarse to fine grained surface texture	The surface texture characteristics reflected in the sample of grooved portland cement concrete from Seymour Johnson AFB are described as follows (1) Equal grooves, 1/8 x 1/8 in. spaced 2 in. apart (2) The surface texture is defined by the grooves and exposed particles of sharp sand and fine aggregate. (3) The combination of grooves and the fine grained surface texture provide a high level of surface drainage The structural characteristics at a depth of 1 1/2 in. below the surface are described as follows (1) The coarse aggregate skeleton consists of fragmented particles of quartz and quartz gravel (2) There is no subsurface drainage capability in the aggregate particles or the matrix	Good

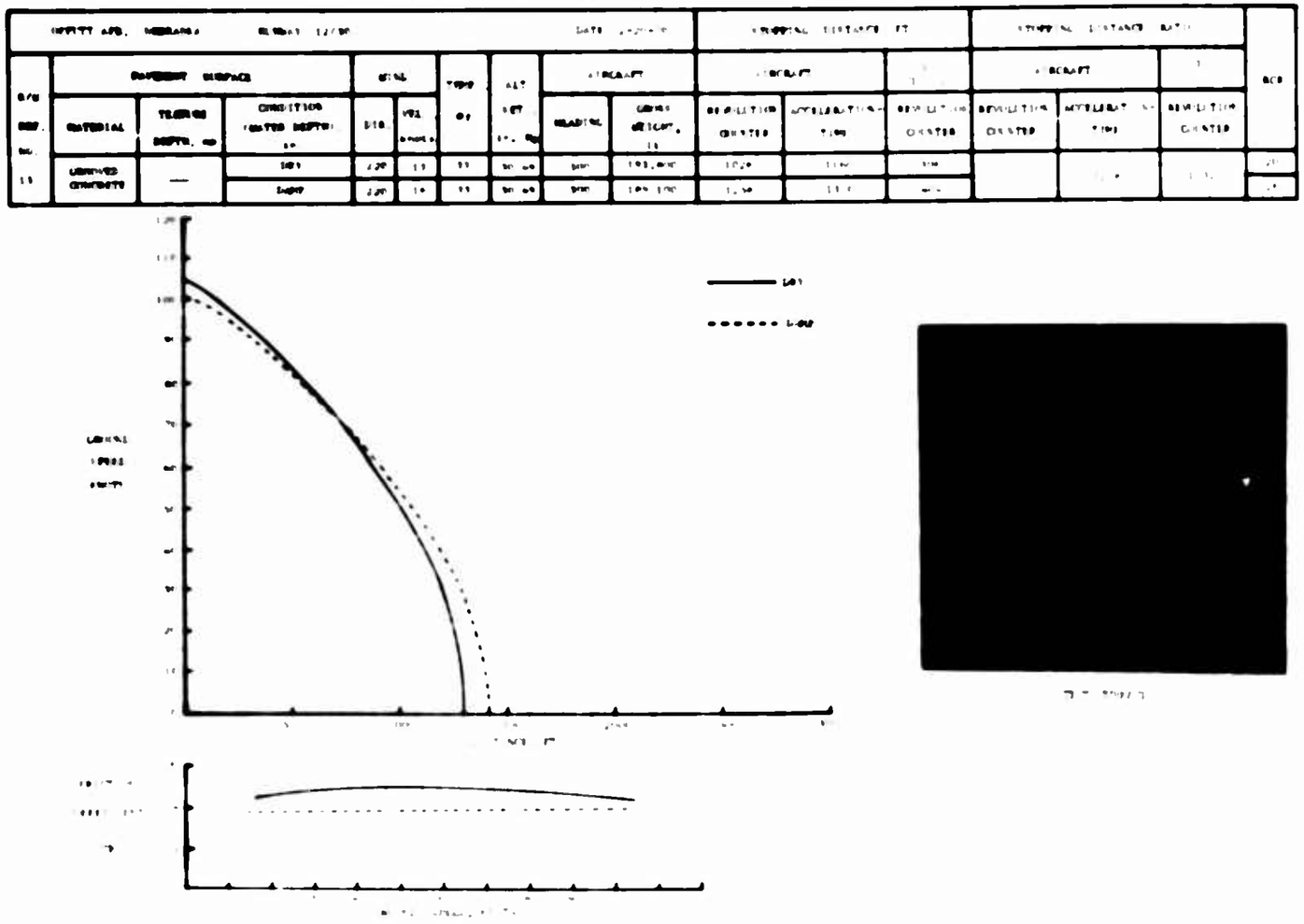
(m) Concluded.

Figure A1.- Continued.



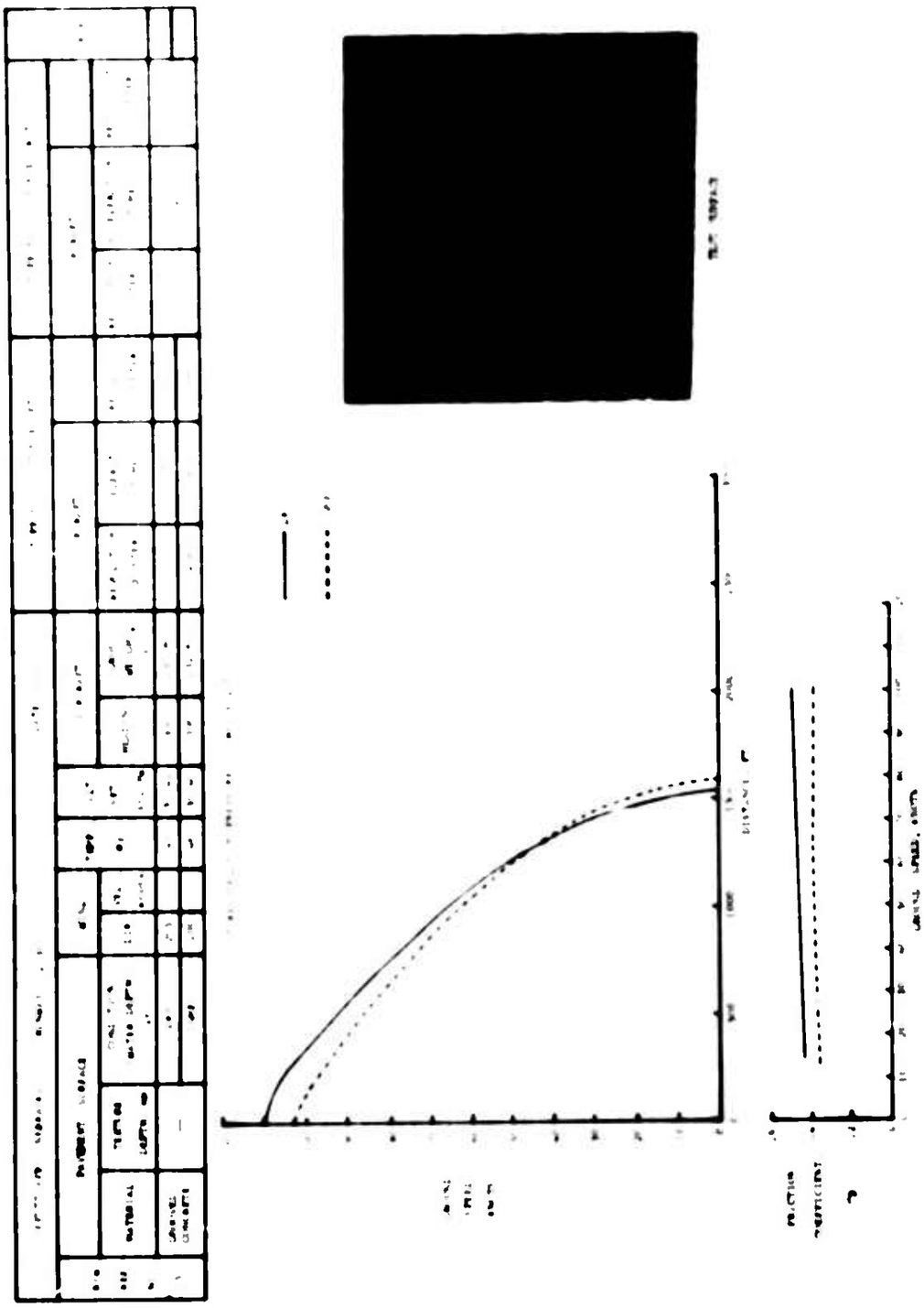
(a) Runway 14; Chicago Midway Airport.

Figure A1.- Continued.



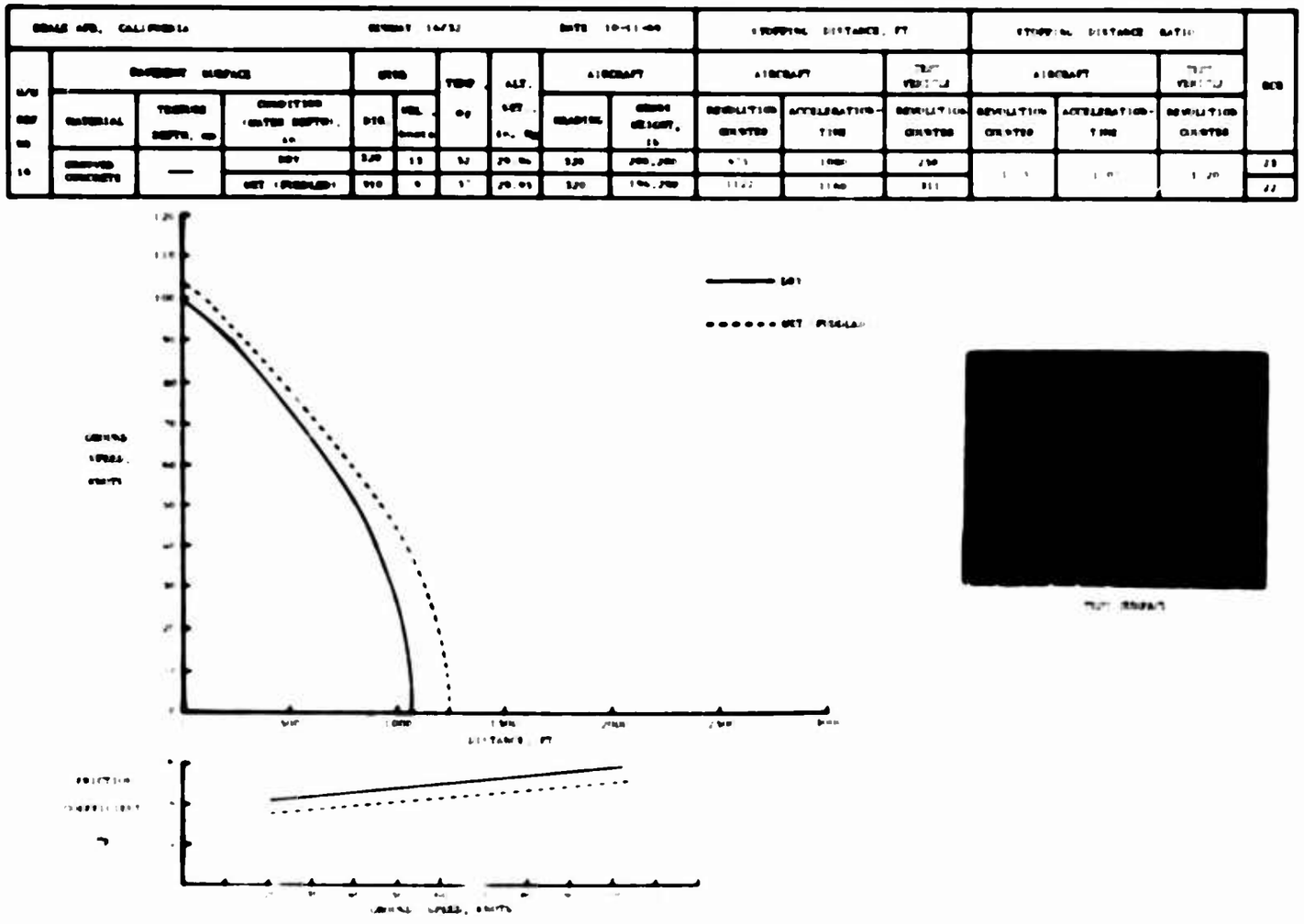
(o) Runway 15; Offutt Air Force Base.

Figure A1.- Continued.



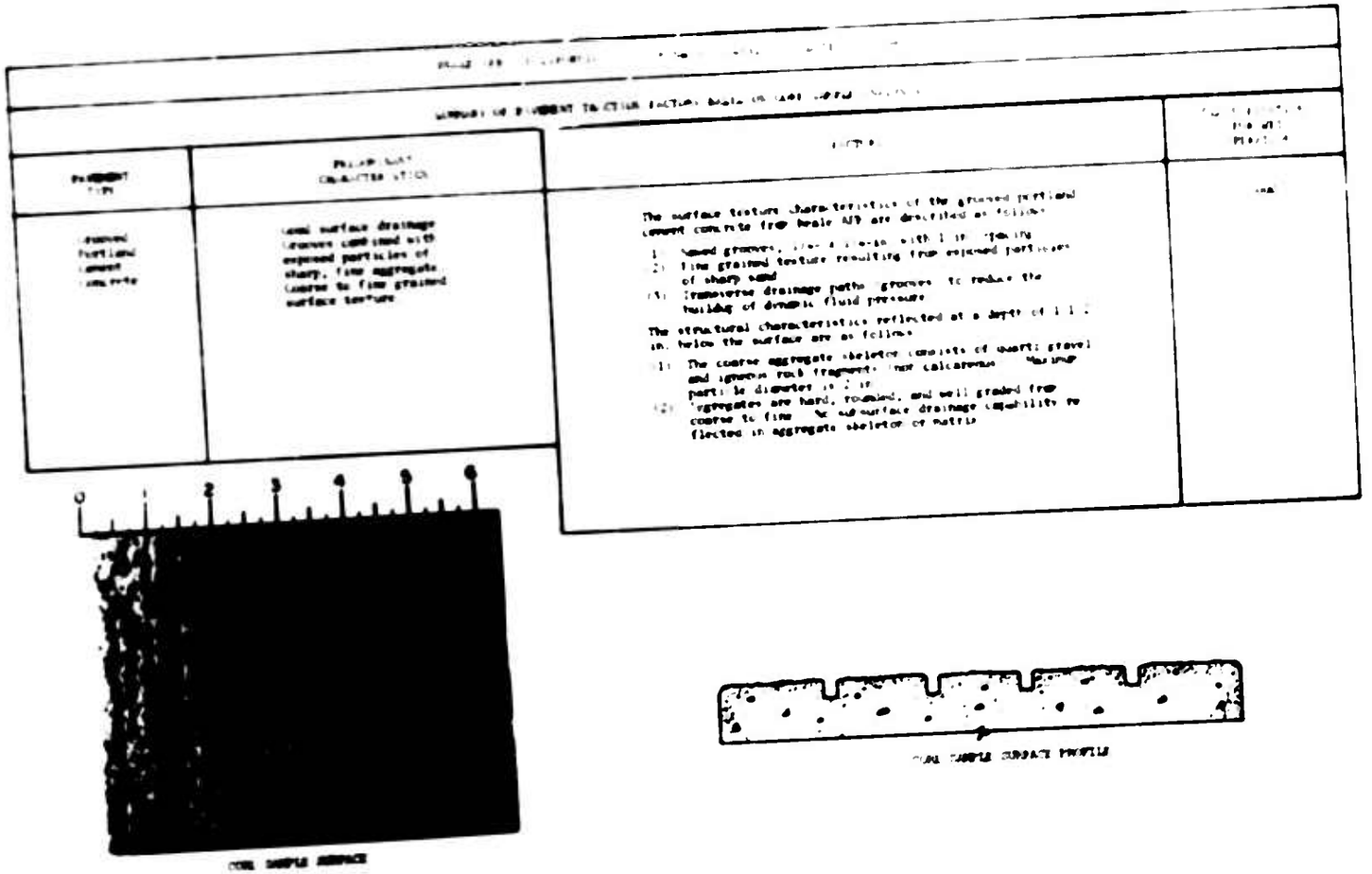
(c) Concluded.

Figure A1.- Continued.



(p) Runway 16; Beale Air Force Base.

Figure A1.- Continued.

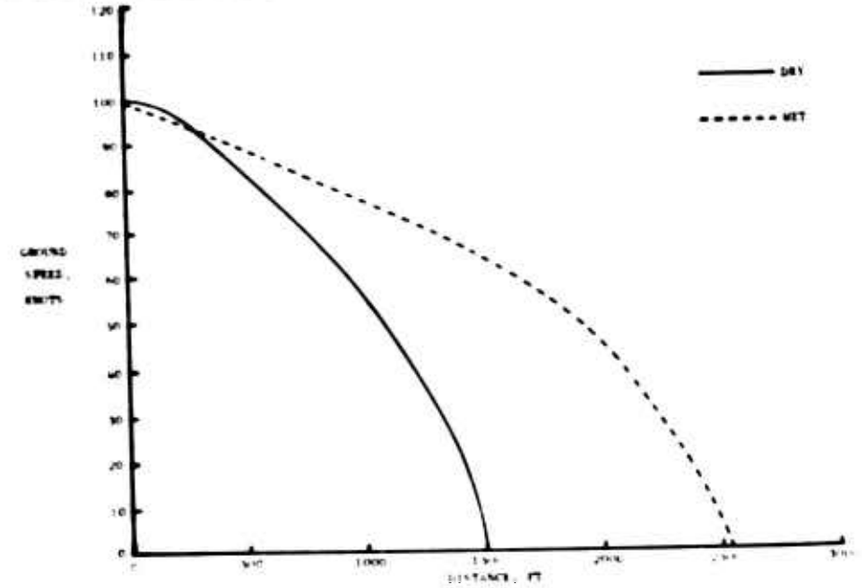


(p) Concluded.

Figure A1.- Continued.

SPANGDAHLEM USAFE BASE, GERMANY				RUNWAY 3/21			DATE 7-31-84		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W END ID.	PAVEMENT SURFACE			WIND		TEMP, °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT			AIRCRAFT			
	MATERIAL	TEXTURE DEPTH, in.	CONDITION (WATER DEPTH, in.)	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
18	RUBBER SEAL	0.214	DRY	030	5	84	30.00	030	194,900	1220	1345	924	.178	.129	.78	17
			WET (.02)	020	6	84	30.00	030	194,900	2410	2350	1650				7

*Based on [illegible] (RR) = 110 ft



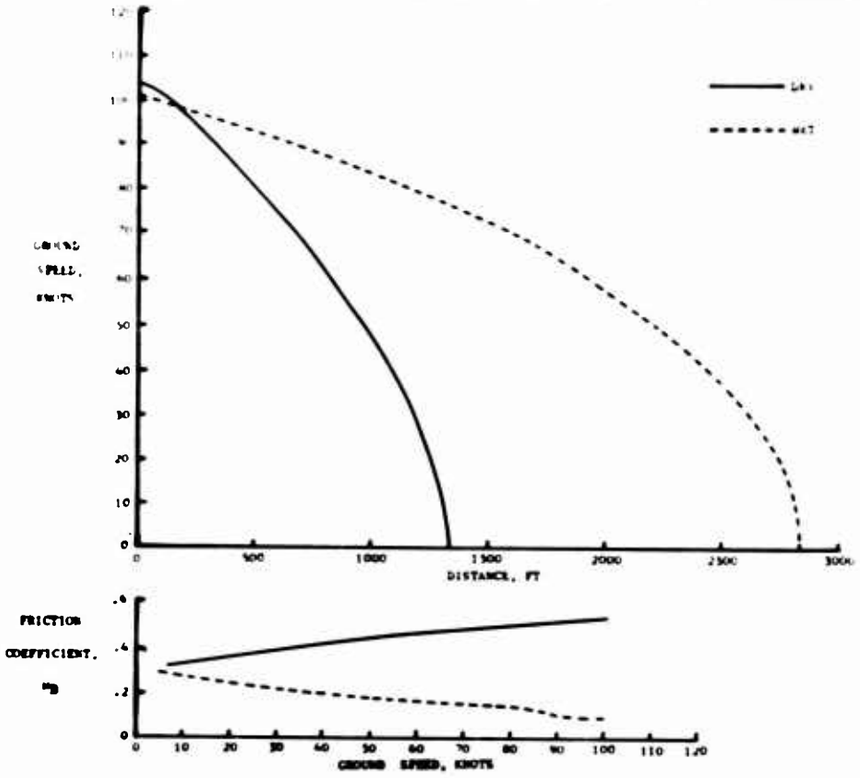


[illegible] AIRCRAFT

(q) Runway 18; Spangdahlem Air Force Base.

Figure A1.- Continued.

R/W GRP NO	PAVEMENT SURFACE			WIND		TEMP °F	ALT. SET in. Hg	AIRCRAFT								
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH, in.)	DIR.	VEL. knots			HEADING	GROSS WEIGHT, lb							
19	ASPHALT	0.200	DRY	180	2	59	29.71	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			WET (.040)	140	2	62	29.73	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]





TEST SURFACE

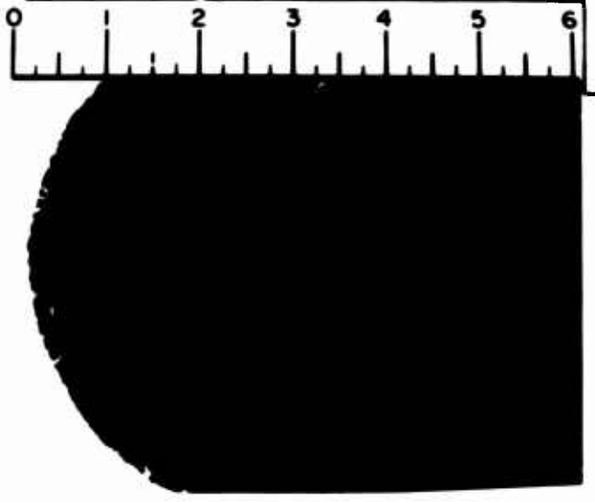
(r) Runway 19; Elmendorf Air Force Base.

Figure A1.- Continued.

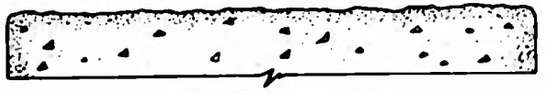
ELMENDORF AFB, ALASKA RUNWAY: 5/23 DATE: 9-19-69

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATION
Asphaltic Concrete	Medium surface drainage. Exposed particles of rounded aggregate. Medium grained texture.	The surface texture characteristics reflected in the sample of asphaltic concrete from Elmendorf AFB are described as follows: (1) The medium grained surface texture is defined primarily by exposed particles of rounded aggregate. (2) The surface texture does offer some surface drainage, but the exposed particles of rounded aggregate are susceptible to thin-film lubrication. The structural characteristics at a depth of 1-1/2 in. below the surface are described as follows: (1) The coarse aggregate skeleton consists of rounded and fragmented particles of igneous rock ranging between 1/8 and 3/4 in. in diameter. (2) The dense graded mix offers no subsurface drainage.	Medium-Poor



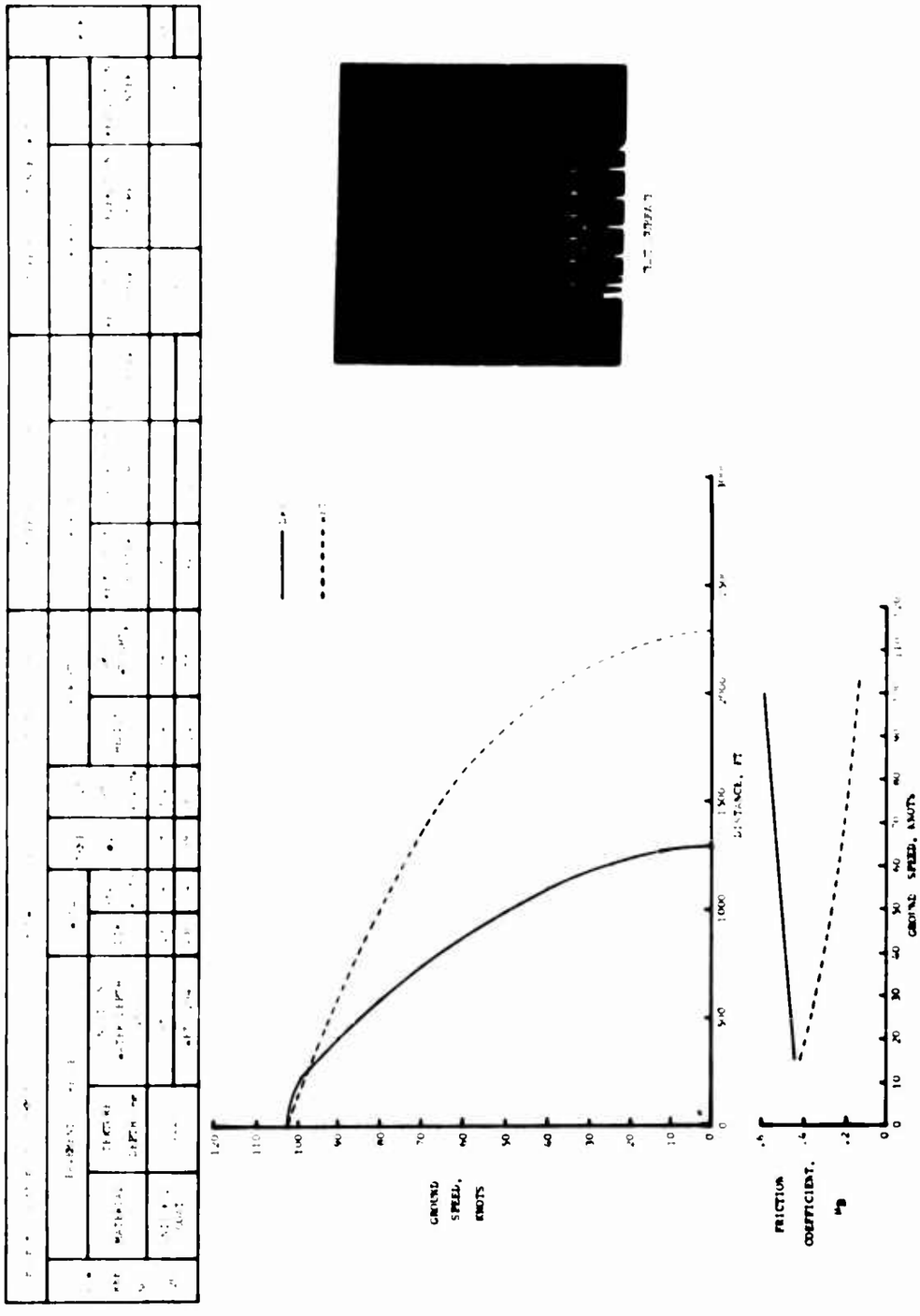
CORE SAMPLE SURFACE



CORE SAMPLE SURFACE PROFILE

(r) Concluded.

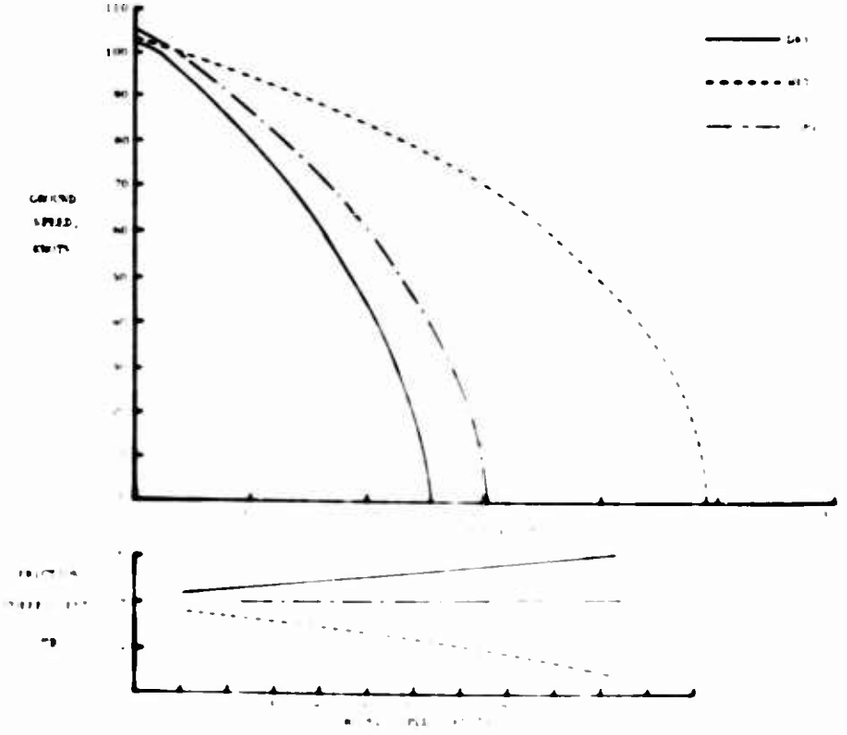
Figure A1.- Continued.



(s) Runway 20; Bitburg Air Force Base.

Figure A1.- Continued.

MYRTLE BEACH AFB. SOUTH CAROLINA													
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP °F	ALT. SET.. in. Hg	AIRCRAFT					PCN
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL. knots			HEADING	GROSS WEIGHT, lb				
21	SLURRY SEAL	0.13	DRY	160	5	59	30.20	210	291,000				
			WET (.04")	240	1	58	30.07	170	291,000				
			DAMP (.01")	190	4	58	30.07	210	291,000				





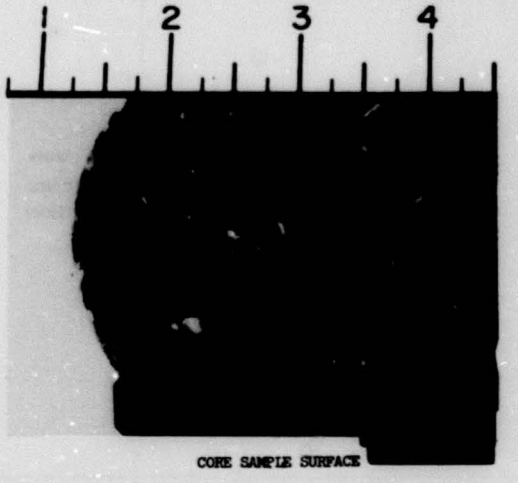
(t) Runway 21; Myrtle Beach Air Force Base.

Figure A1.- Continued.

MYRTLE BEACH AFB, SOUTH CAROLINA RUNWAY: 17/35 DATE: 10-8-69

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATION
Asphaltic Concrete	Medium surface drainage. Exposed particles of sharp aggregate. Medium grained surface texture.	The surface texture characteristics of the sample of asphaltic concrete from Myrtle Beach AFB are described as follows: (1) The medium grained surface texture is defined by small (less than 1/4 in.) fractured particles of quartz. Aggregate exposure is facilitated by an erosion of the sand-asphalt matrix. (2) The interparticle depressions provide a low level of surface drainage. The structural characteristics below the surface are described as follows: (1) The aggregate skeleton consists of fractured and rounded particles of quartz ranging between 1/4 and 3/4 in. in diameter. (2) The dense graded mix offers no subsurface drainage.	Medium-Good



CORE SAMPLE SURFACE



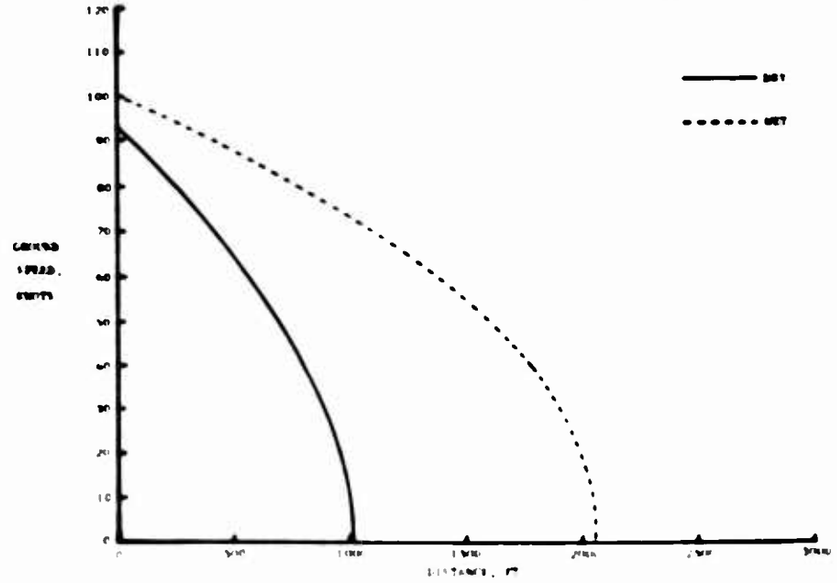
CORE SAMPLE SURFACE PROFILE

(t) Concluded.

Figure A1.- Continued.

RUNWAY DIRECTION	PAVEMENT SURFACE			WIND		TEMP	ALT SET	AIRCRAFT		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
	MATERIAL	TEXTURE DEPTH, in	CONDITION (WATER DEPTH), in.	DIR.	VEL, knots	°F	in. Hg	HEADING	GROSS WEIGHT, lb	AIRCRAFT			AIRCRAFT			
										REVOLUTION CRYSTEX	ACCELERATION-TIME	REVOLUTION CRYSTEX	REVOLUTION CRYSTEX	ACCELERATION-TIME	REVOLUTION CRYSTEX	
22	1/8" GRIT COAT	0.270	DRY	140	5	72	30.10	210	195,500	1355	1170	320	1.000	1.010	1.0	—
			WET (.05)	140	5	72	30.10	210	198,200	2070	2040	615				—

*Based on V_{REF} + 110 kt





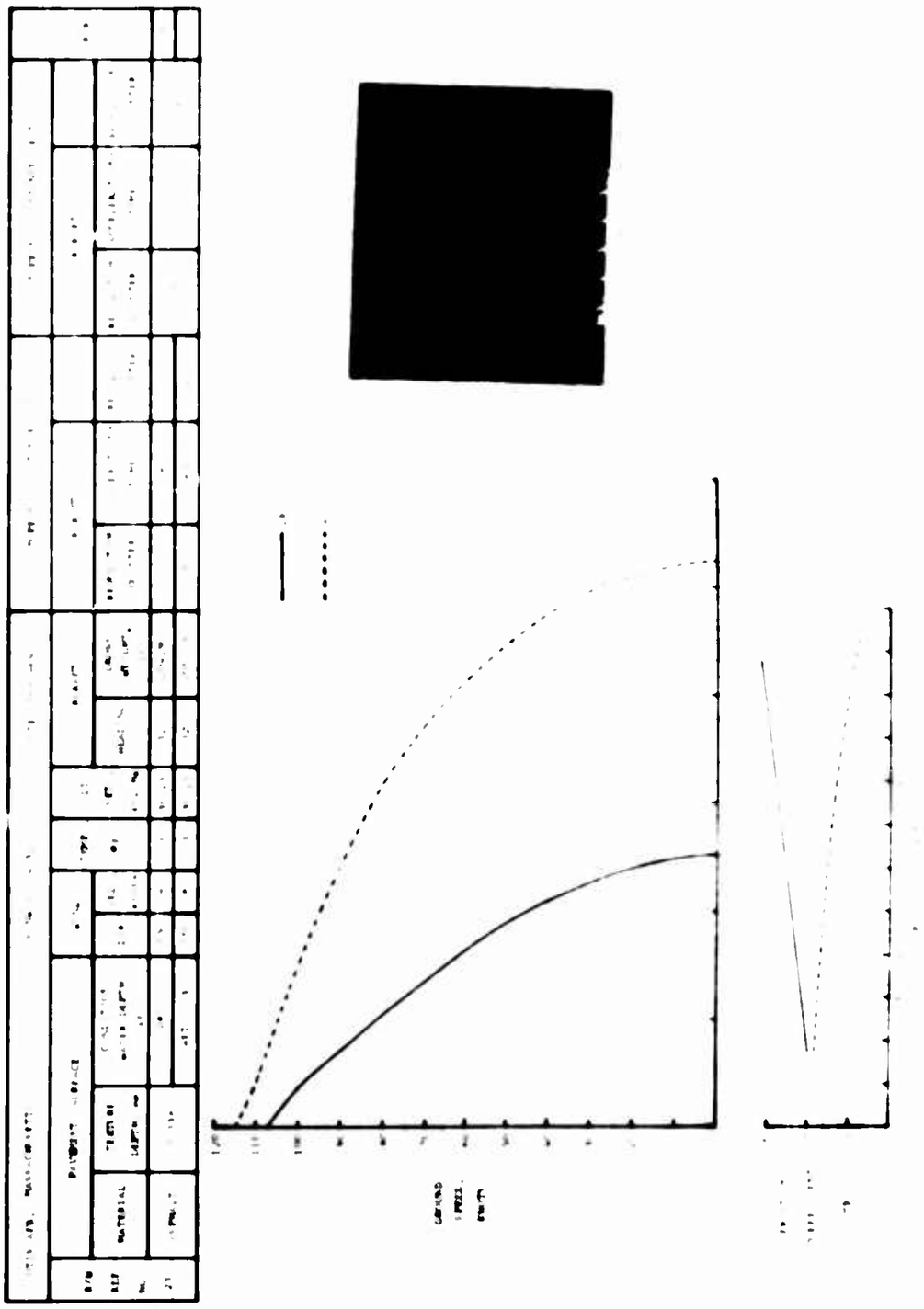
(u) Runway 22; Waddington Royal Air Force Base.

Figure A1.- Continued.



(u) Concluded.

Figure A1.- Continued.

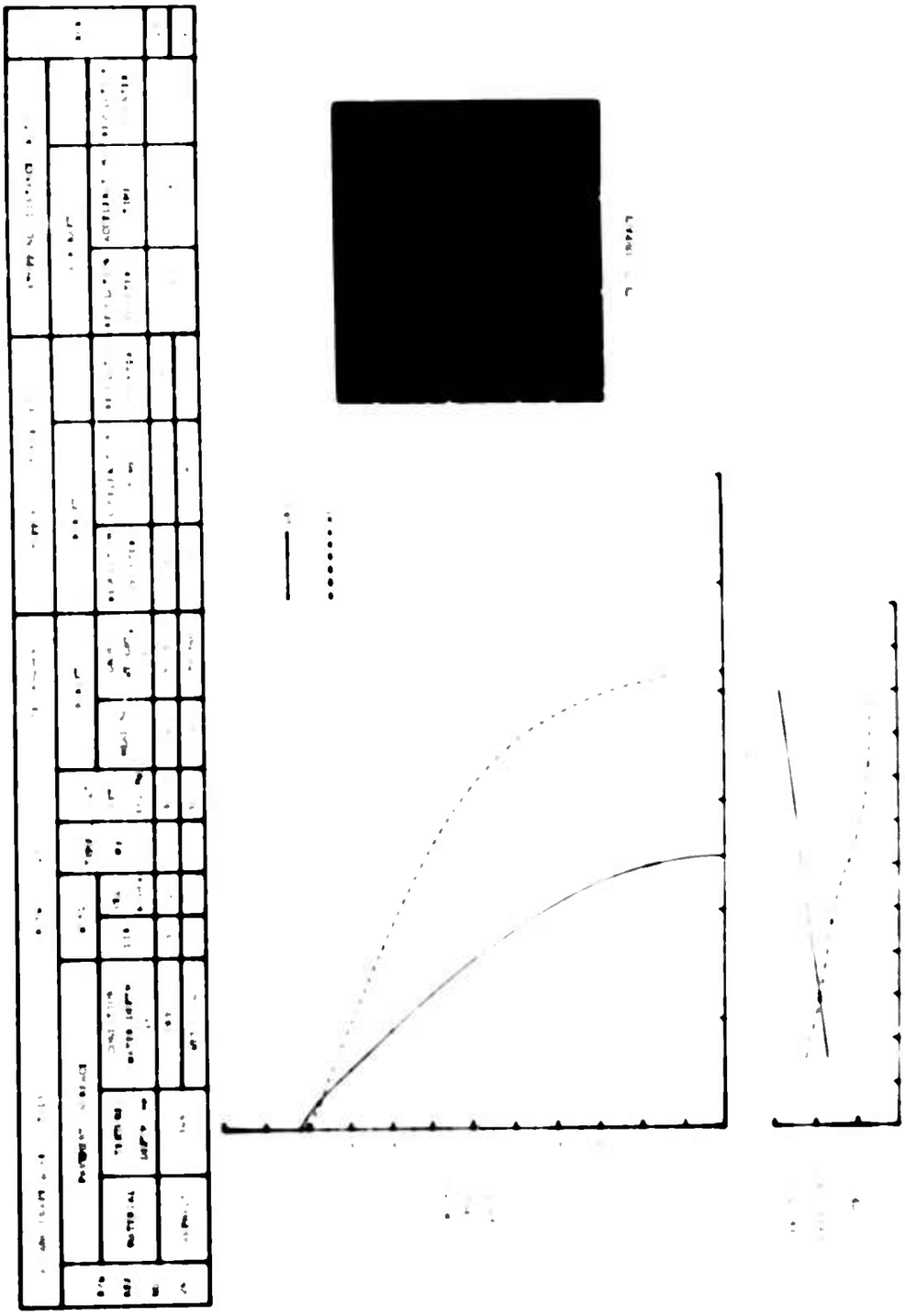


(v) Runway 23; Otis Air Force Base.

Figure A1.- Continued.

(v) Concluded.

Figure A1.- Continued.

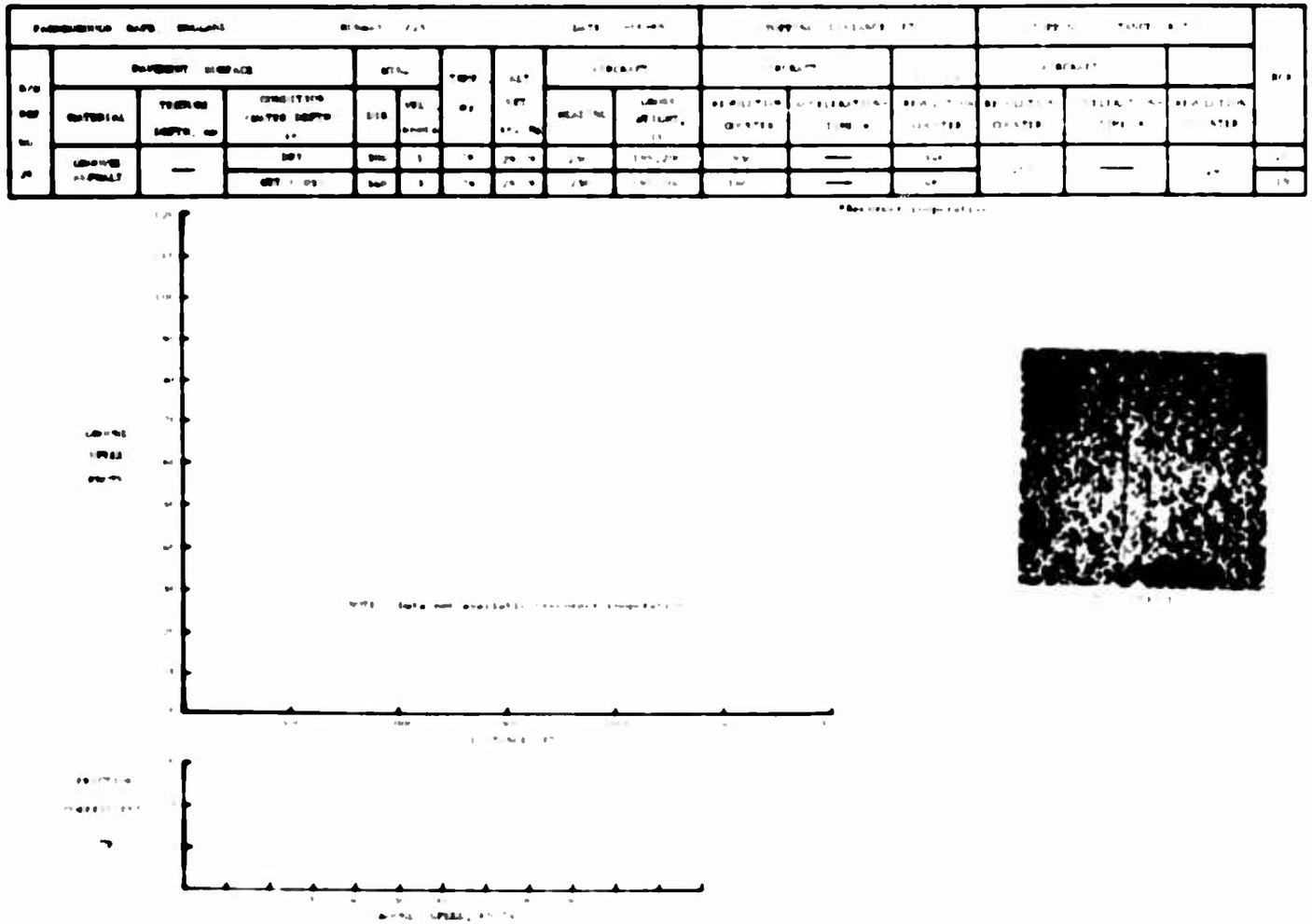


(w) Runway 34; Aviano Air Force Base.

Figure A1.- Continued.

(x) Runway 25; Alconbury Air Force Base.

Figure A1.- Continued.



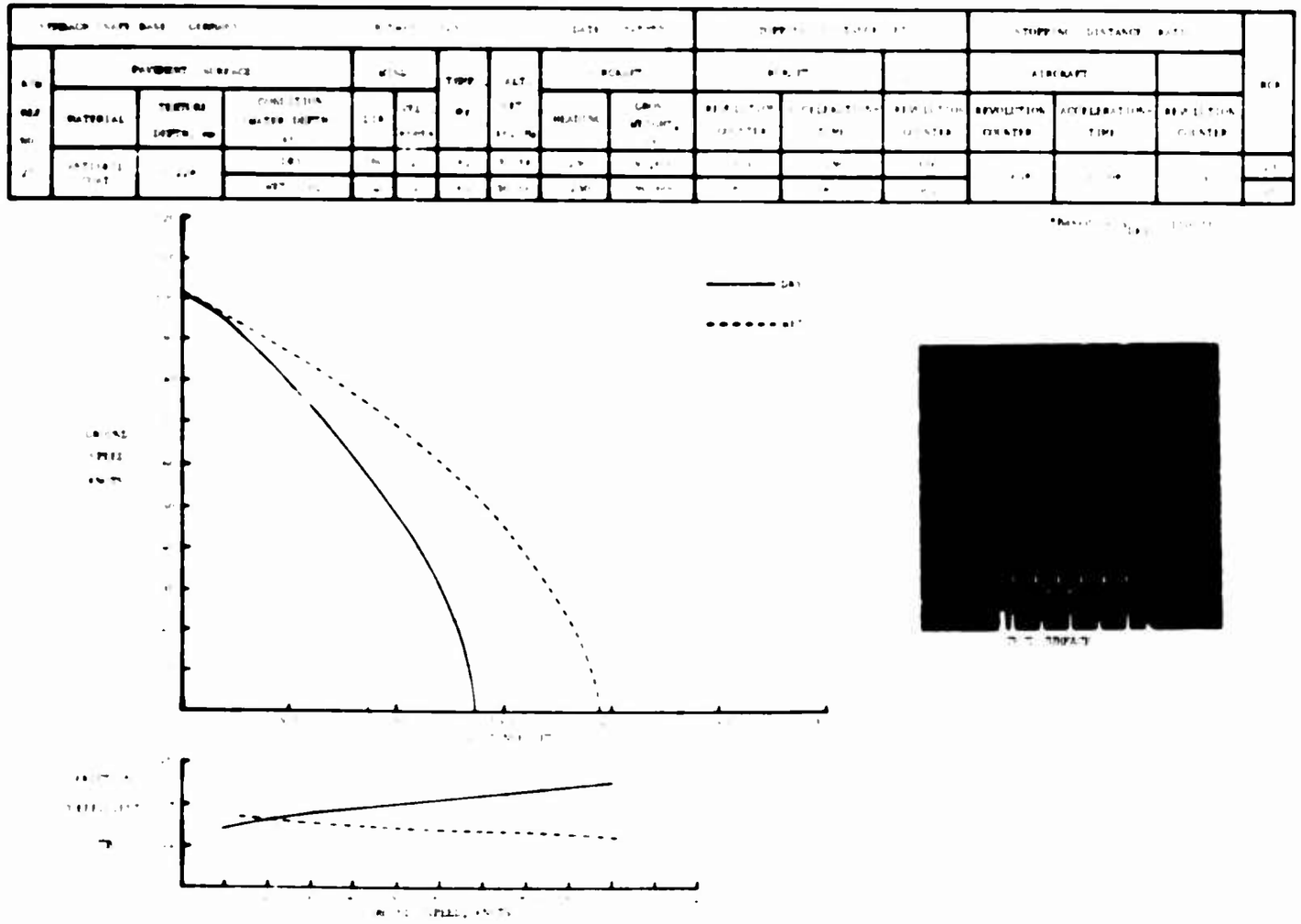
(y) Runway 26; Farnborough Air Force Base.

Figure A1.- Continued.



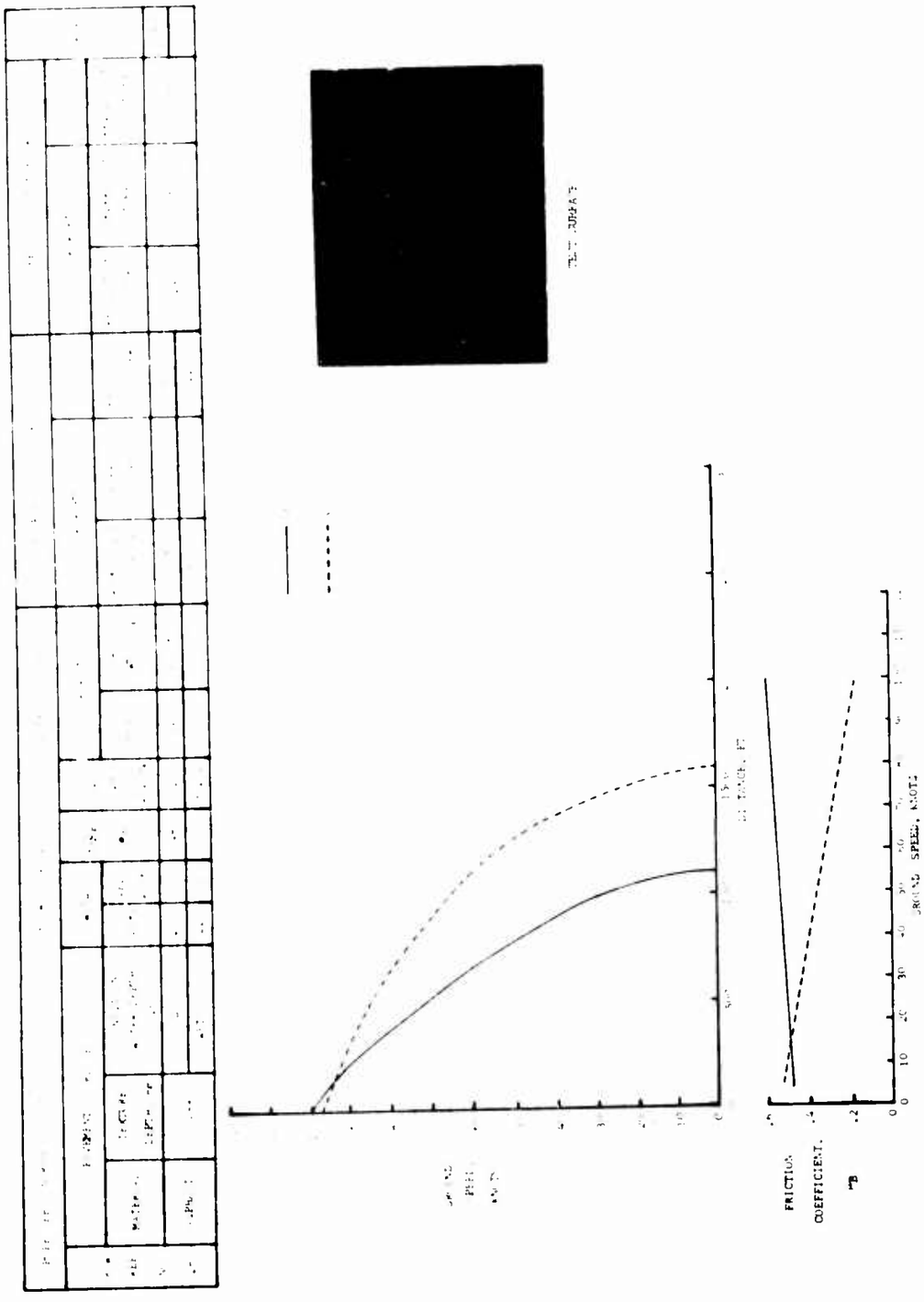
(y) Concluded.

Figure A1.- Continued.



(z) Runway 27; Sembach Air Force Base.

Figure A1.- Continued.



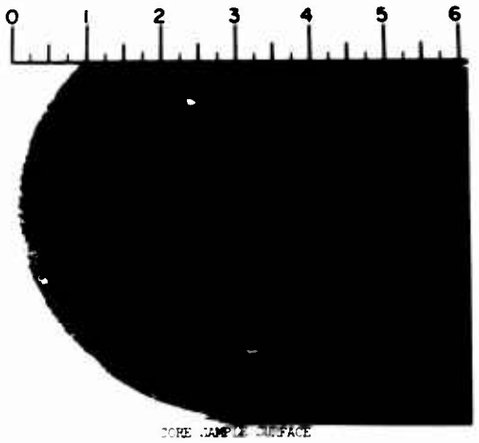
(aa) Runway 28; Pope Air Force Base.

Figure A1.- Continued.

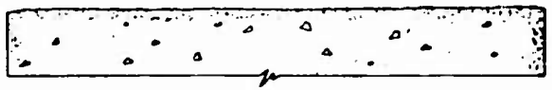
POPE AFB, NORTH CAROLINA RUNWAY [illegible]

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATIONS
Asphaltic Concrete	Poor surface drainage. Exposed particles of fine sand. Fine grained surface texture.	The surface texture characteristics reflected in the sample of asphaltic concrete from Pope AFB are described as follows: (1) The surface texture is defined by the sand asphalt matrix that was forced to the surface during compaction. There is very little particle angularity extending above the matrix. (2) The fine grained surface texture offers little or no surface drainage. The structural characteristics at a depth of 1 1/2 in. below the surface are described as follows: 1) The aggregate skeleton consists of a mixture of rounded and fragmented particles of quartz and quartz gravel ranging between 1/4 and 1 in. in diameter. (2) The dense graded mix offers no subsurface drainage.	Medium Poor



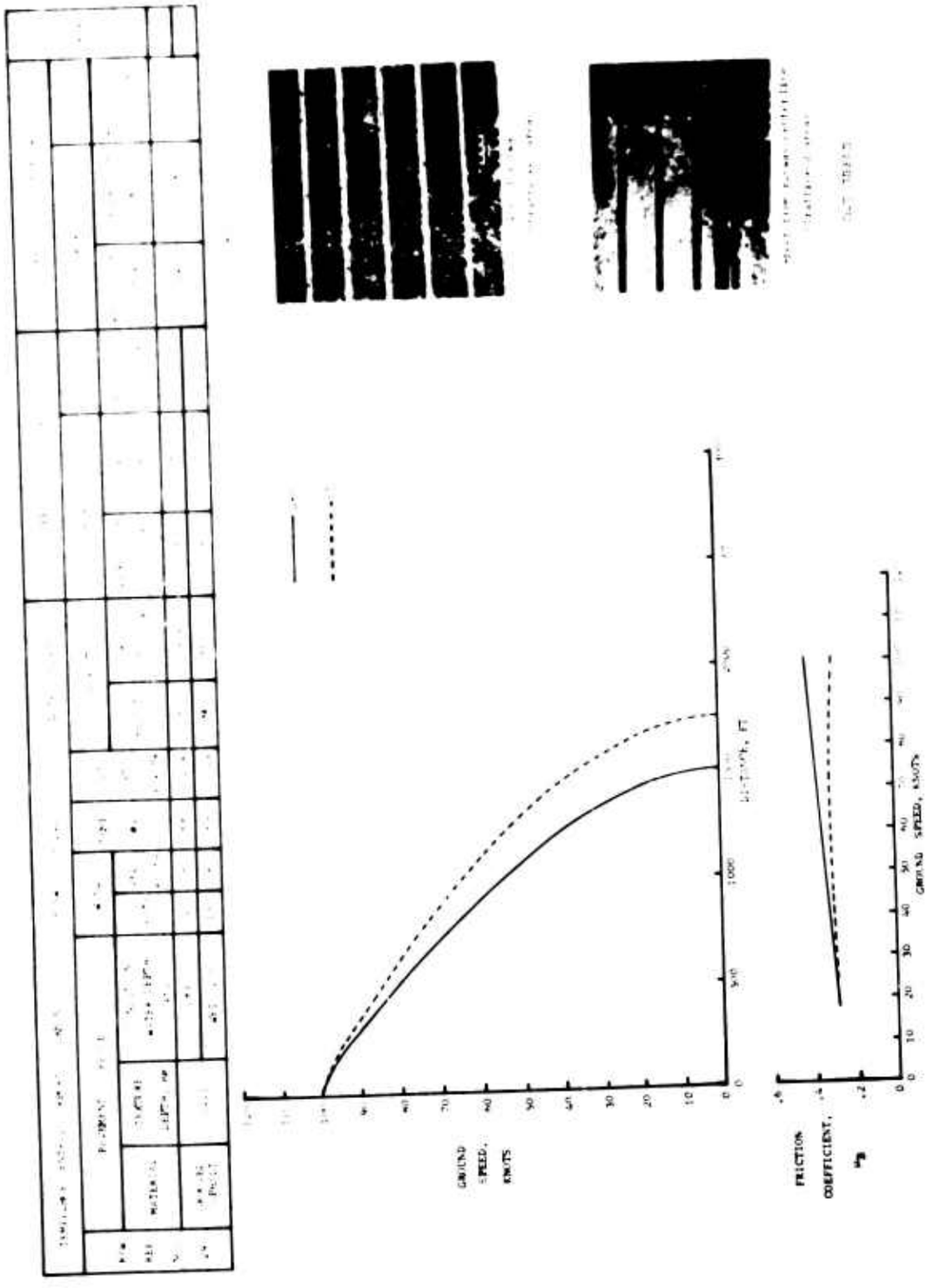
CORE SAMPLE SURFACE



[illegible]

(aa) Concluded.

Figure A1.- Continued.

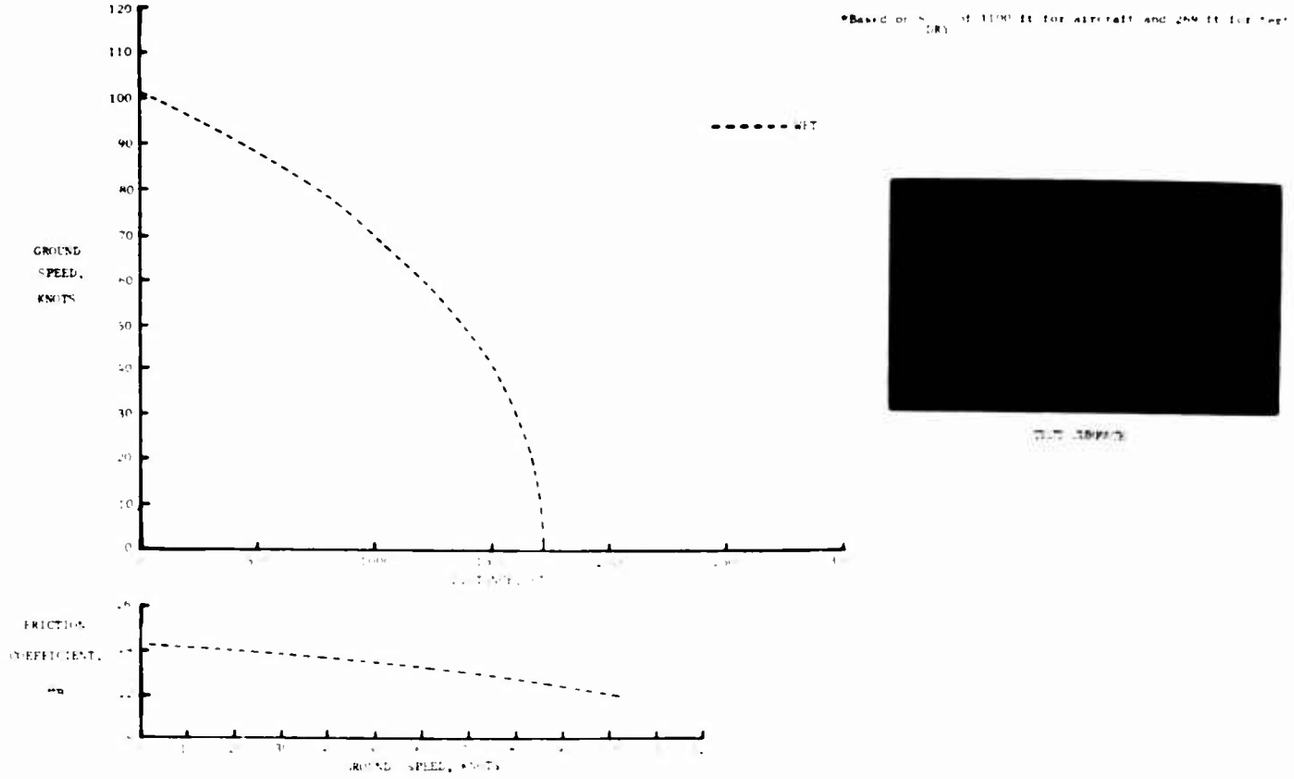


(bb) Runway 29; Tempelhof Central Airport.

Figure A1.- Continued.

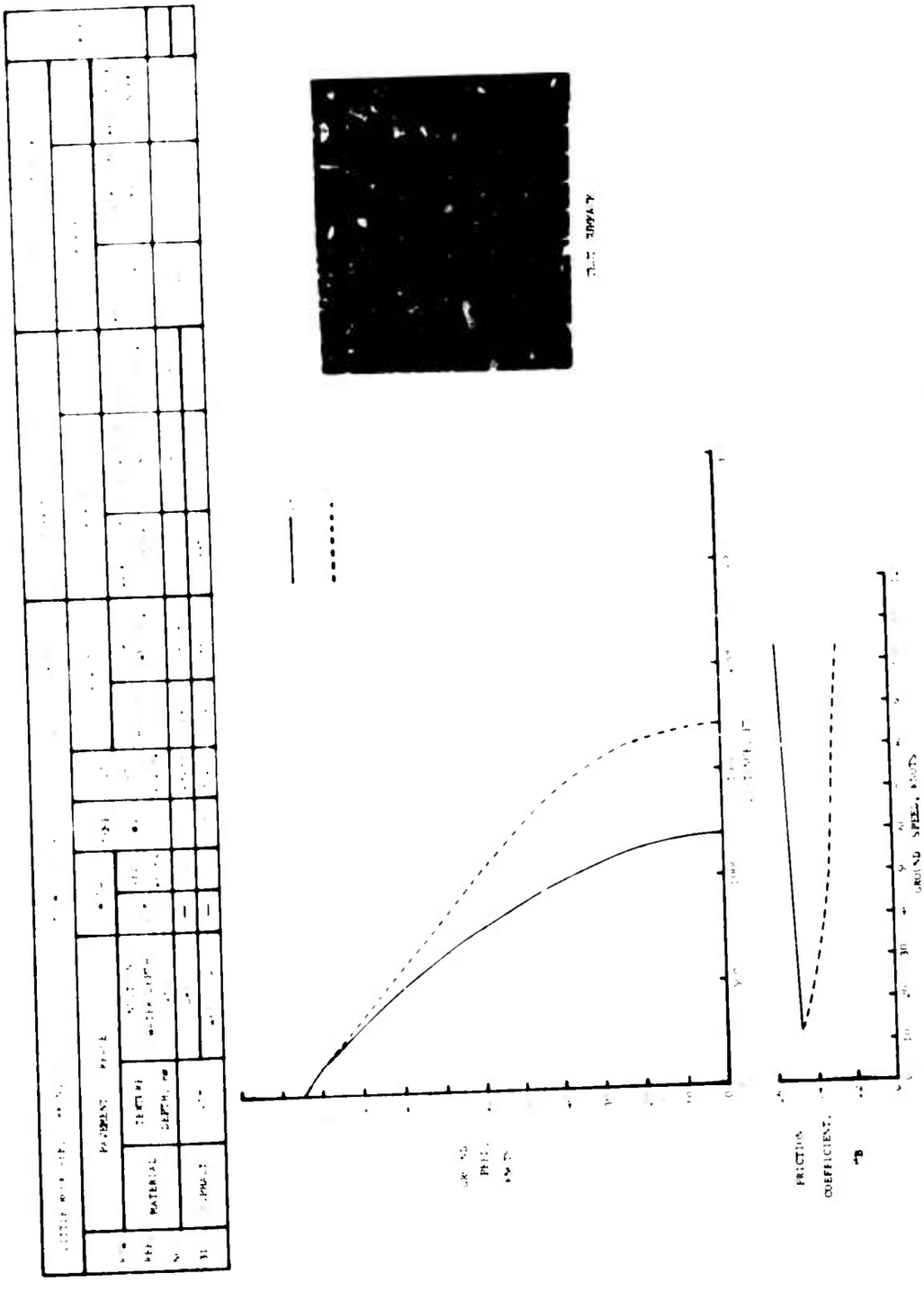
McCHORD AFB, WASHINGTON			RUNWAY 16/34		DATE 2-17-70				STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/M REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT		[illegible]	AIRCRAFT		[illegible]	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
30	ASPHALT	——	NATURAL RAIN (.02)	170	-	42	30.19	160	198,000	1610	1670	523	1.07*	1.51*	1.06*	15

*Based on [illegible] of 1000 ft for aircraft and 250 ft for test unit in [illegible]



(cc) Runway 30; McChord Air Force Base.

Figure A1.- Continued.



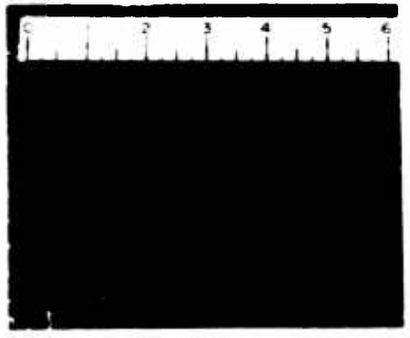
(dd) Runway 31; Little Rock Air Force Base.

Figure A1.- Continued.

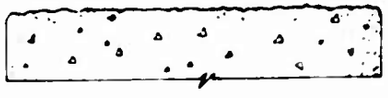
LITTLE ROCK, ARKANSAS

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS		
Asphaltic Concrete	Medium surface drainage. Exposed particles of sharp or fractured aggregate. Medium grained surface texture.	The surface texture characteristics of the asphaltic concrete from Little Rock AFB are described as follows: 1. The medium grained surface texture is defined by exposed particles of crushed aggregate. 2. The surface texture offers some surface drainage. The medium grained surface texture is a result of exposed particles of crushed rock. The structural characteristics below the surface are described as follows: 1. The coarse aggregate skeleton consists of fragmented particles of igneous rock well graded [illegible] ing between 1.0 and 3.4 in. in diameter. 2. The dense graded overlay offers [illegible]	Medium

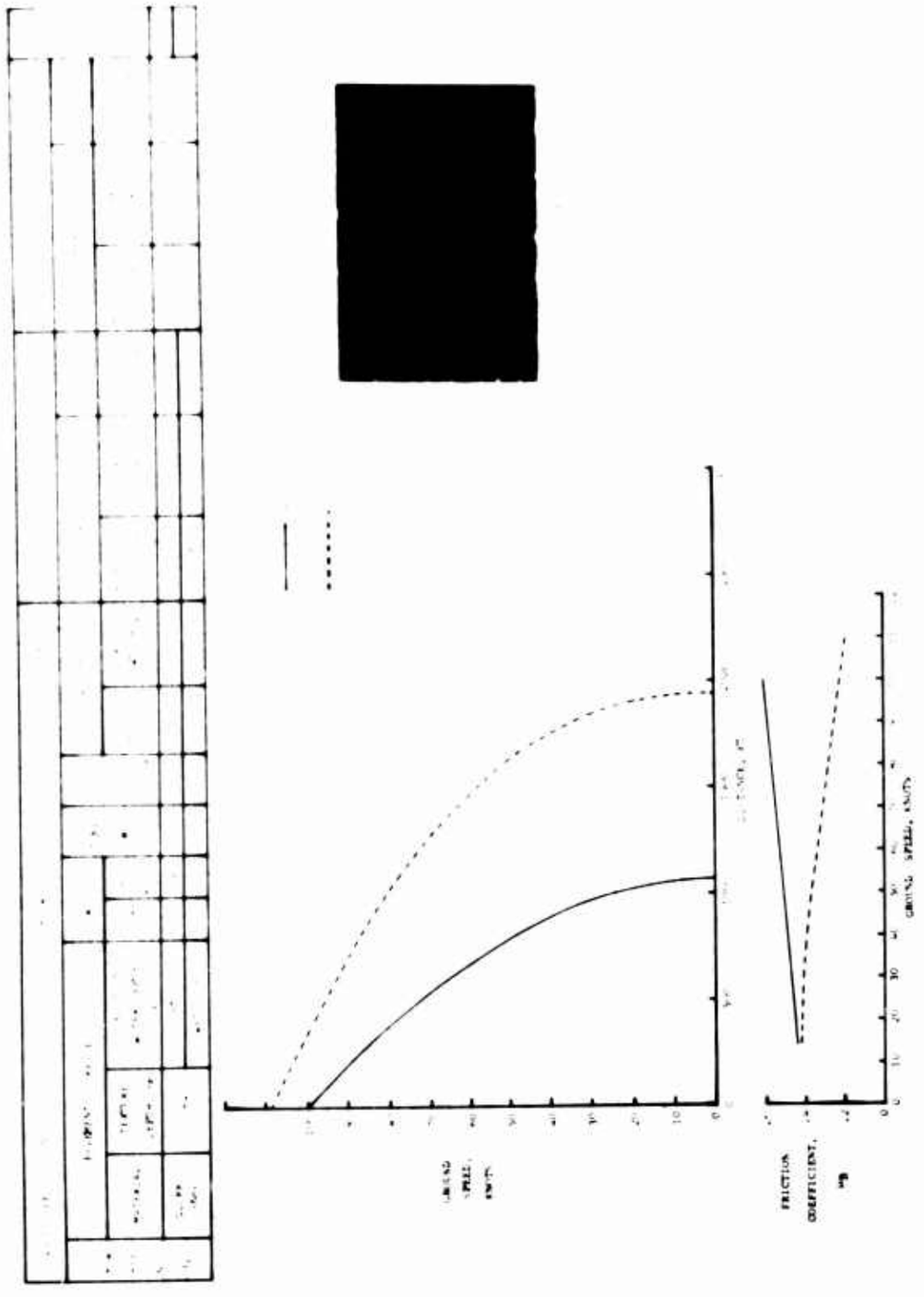


CORE SAMPLE SURFACE



(dd) Concluded.

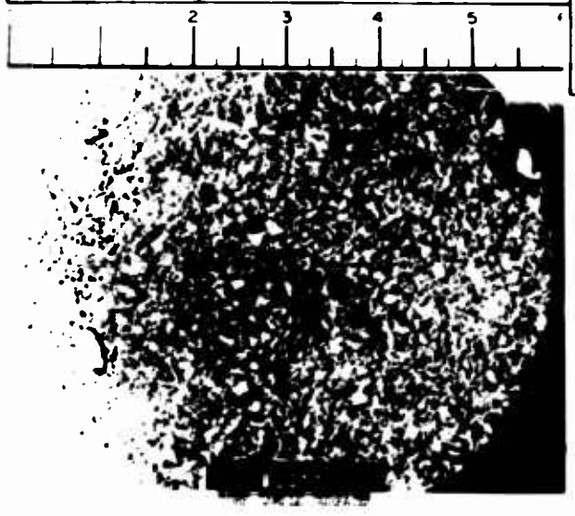
Figure A1.- Continued.

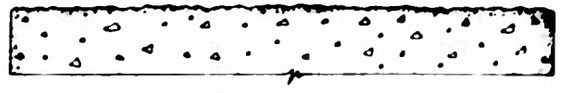


(ee) Runway 32; Scott Air Force Base.

Figure A1.- Continued.

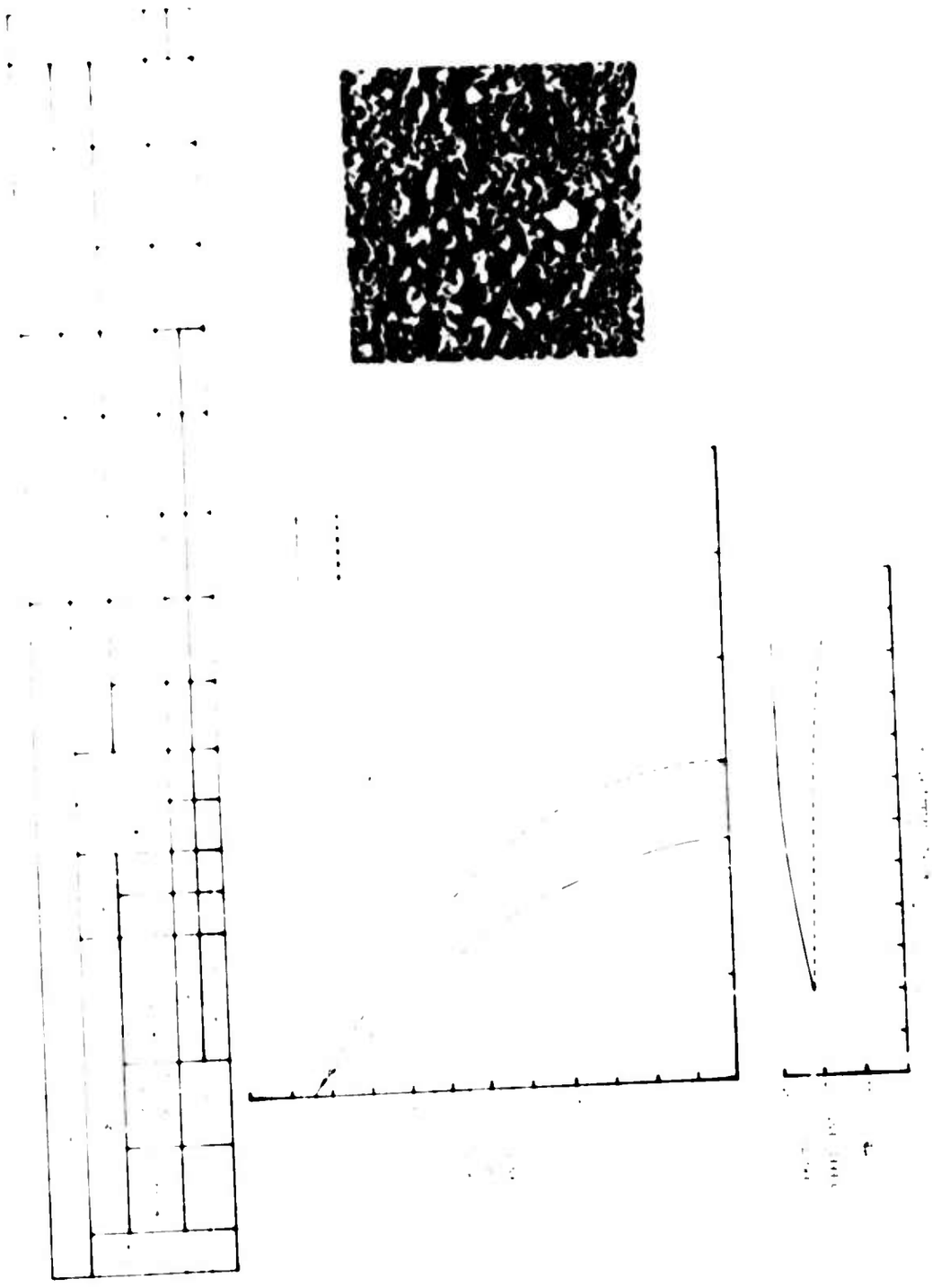
PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS		
Asphaltic Concrete	Medium to poor surface drainage. Exposed particles of limestone reflecting some wear or polish. Medium grained surface texture.	The surface texture characteristics reflected in the sample of asphaltic concrete from Scott AFB are described as follows: (1) The surface texture is defined by the exposed particles of crushed limestone with little particle angularity above the surface. (2) The relatively smooth surface, resulting from the asphalt matrix and aggregate wear, offers very little surface drainage. The structural characteristics reflected at a depth of 1 1/2 in. below the surface are described as follows: (1) The coarse aggregate skeleton consists of fragmented particles of limestone (calcareous rock) ranging between 1/4 and 1 in. in diameter. 2. The dense graded mix offers no subsurface drainage.	Medium Coarse





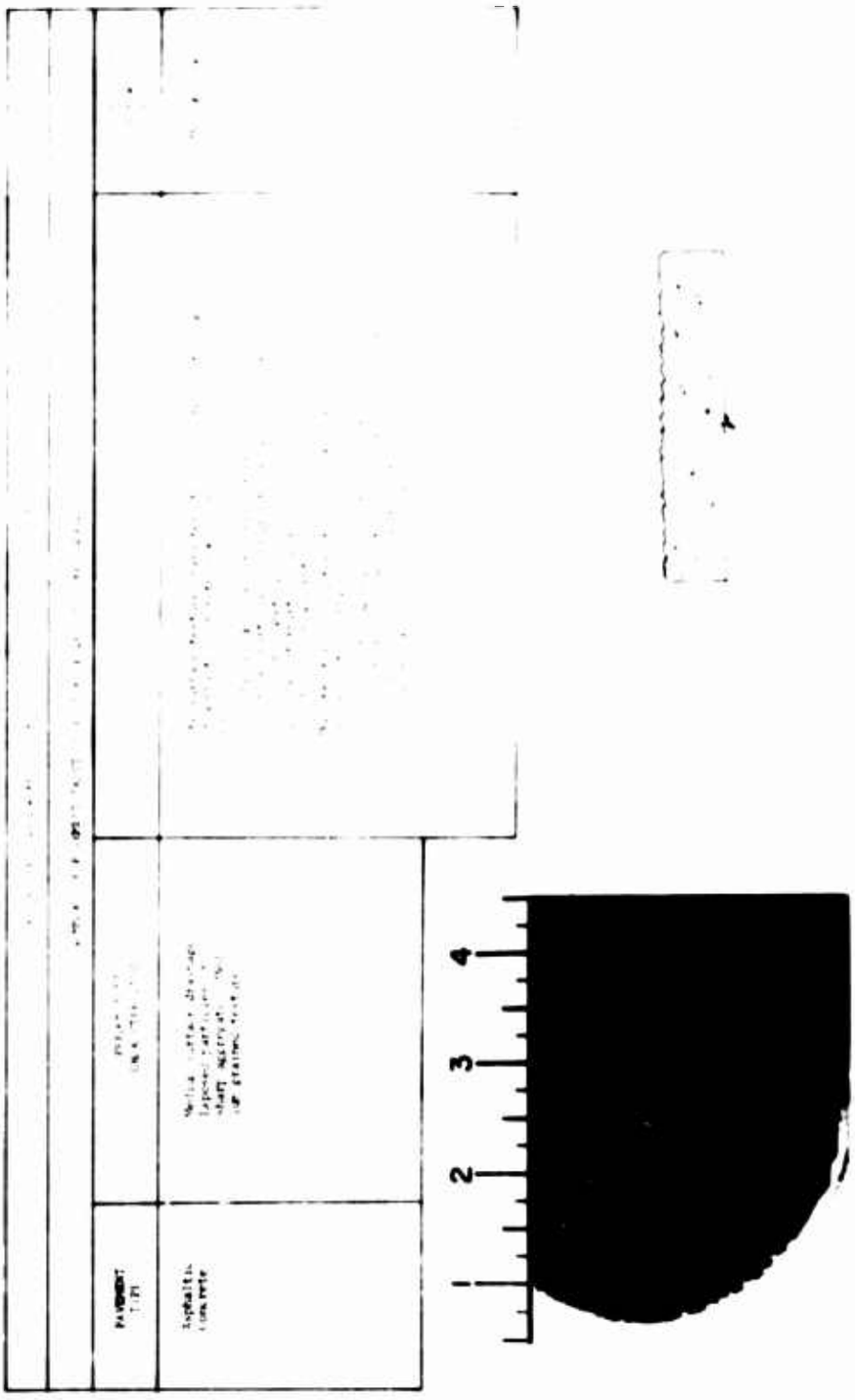
(ee) Concluded.

Figure A1.- Continued.



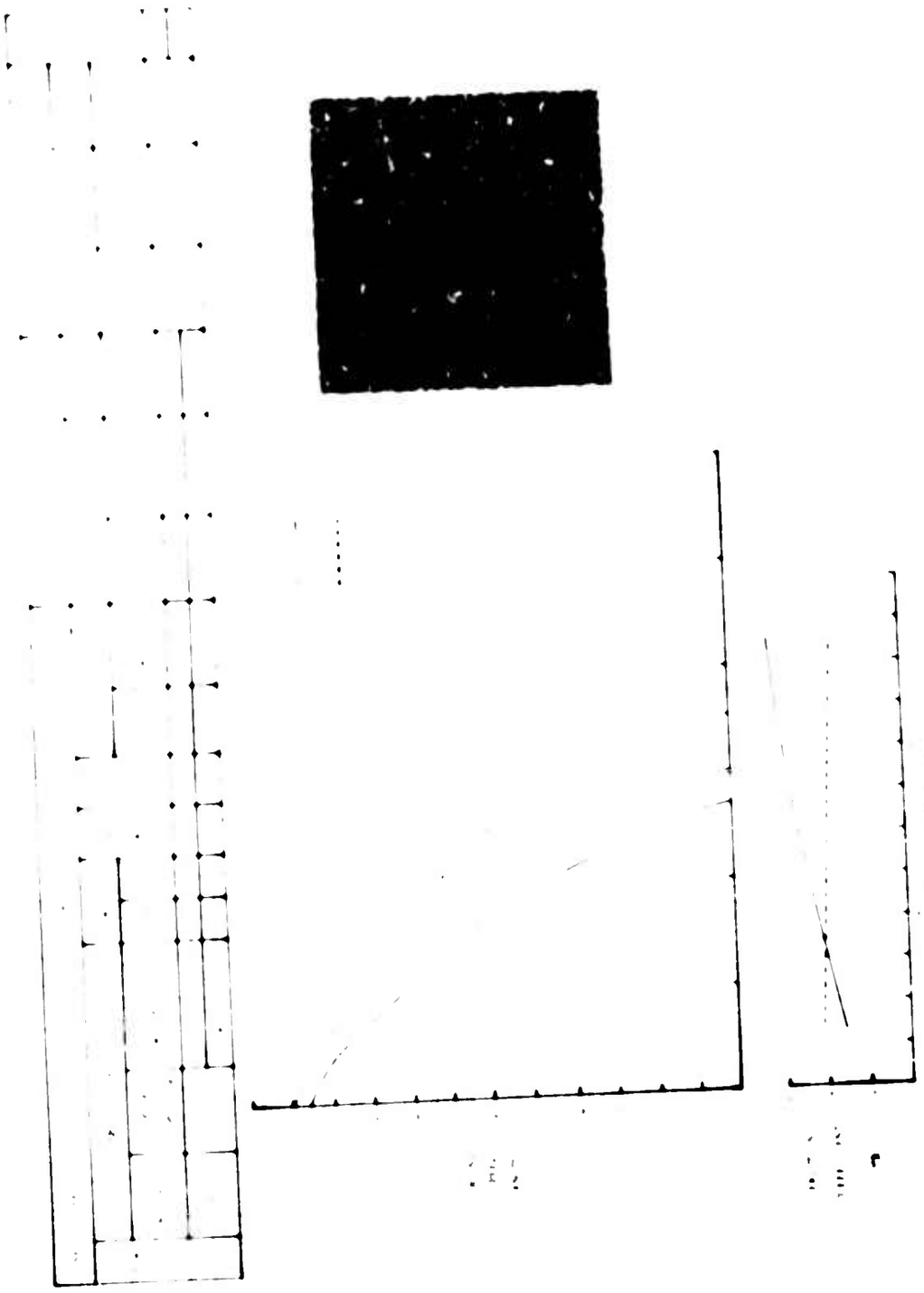
(ff) Runway 33: Dover Air Force Base.

Figure A1.- Continued.



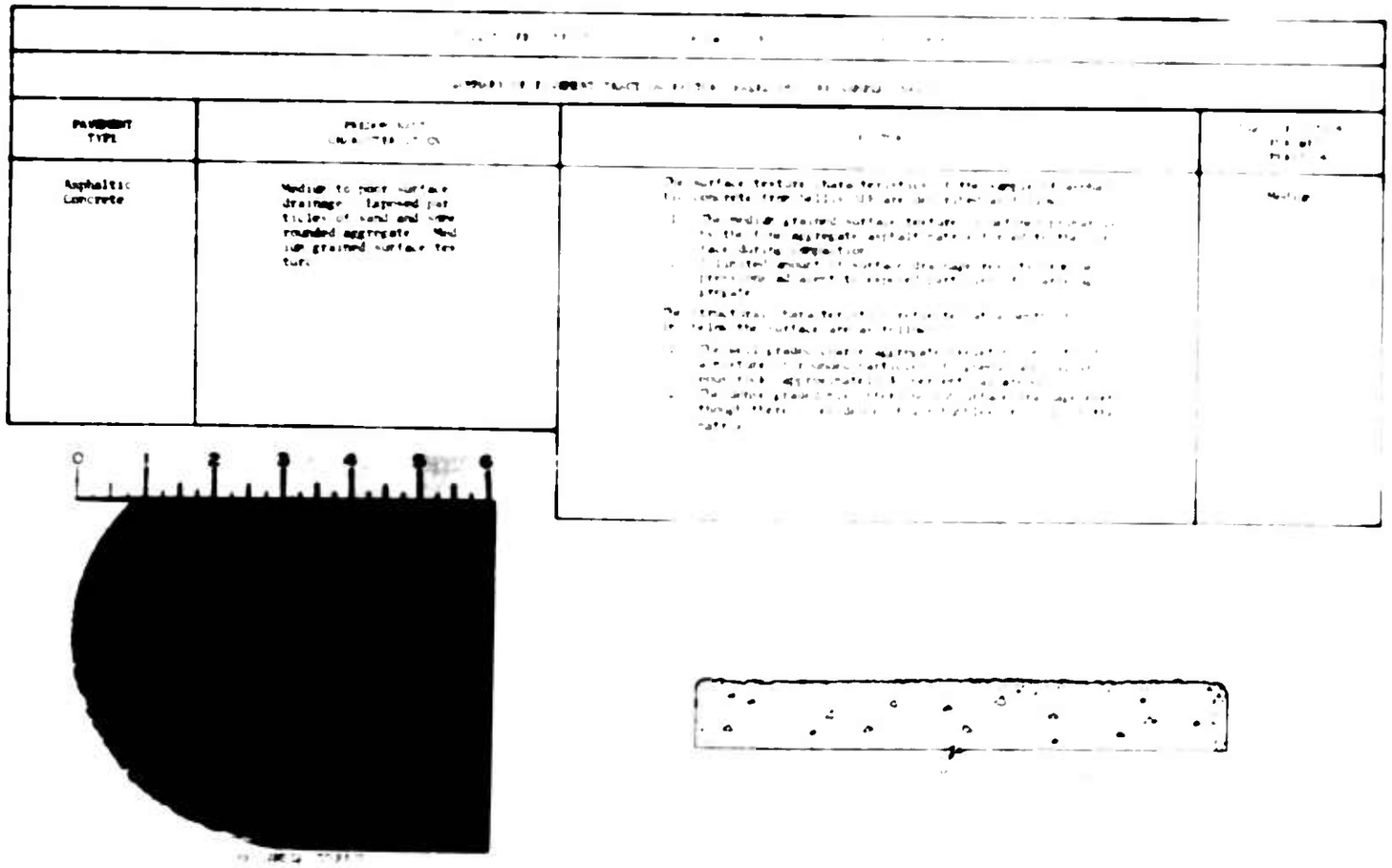
(ff) Concluded.

Figure A1.- Continued.



(gg) Runway 34: Nellis Air Force Base.

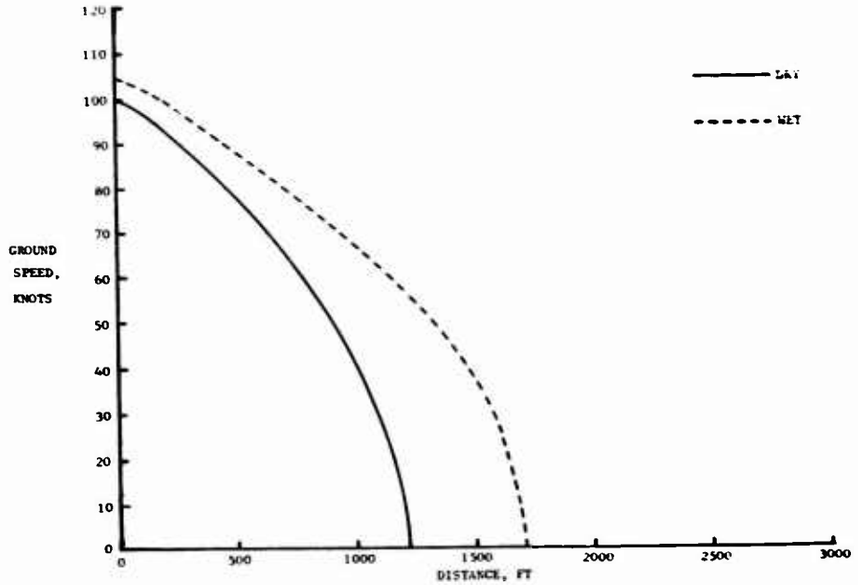
Figure A1.- Continued.

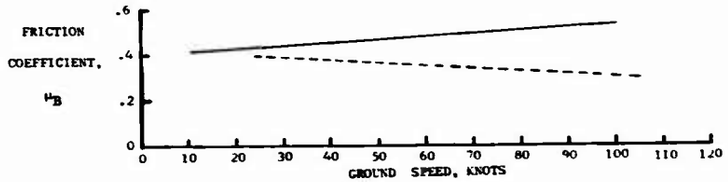


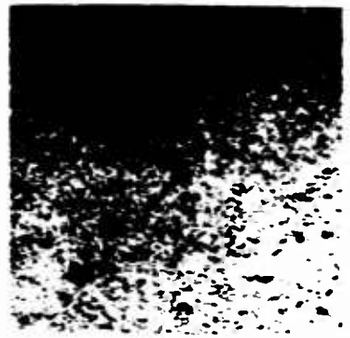
(gg) Concluded.

Figure A1.- Continued.

NASA - WALLOPS STATION, VIRGINIA				RUNWAY 10/28			DATE [illegible]		STOPPING DISTANCE, FT			[illegible]			
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT			AIRCRAFT			[illegible]
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER
35	SLURRY SEAL	0.295	DRY	280	10	76	30.03	100	184,400	1040	11[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			WET (.02)	—	0	76	30.15	100	184,400	1330	1500	[illegible]			





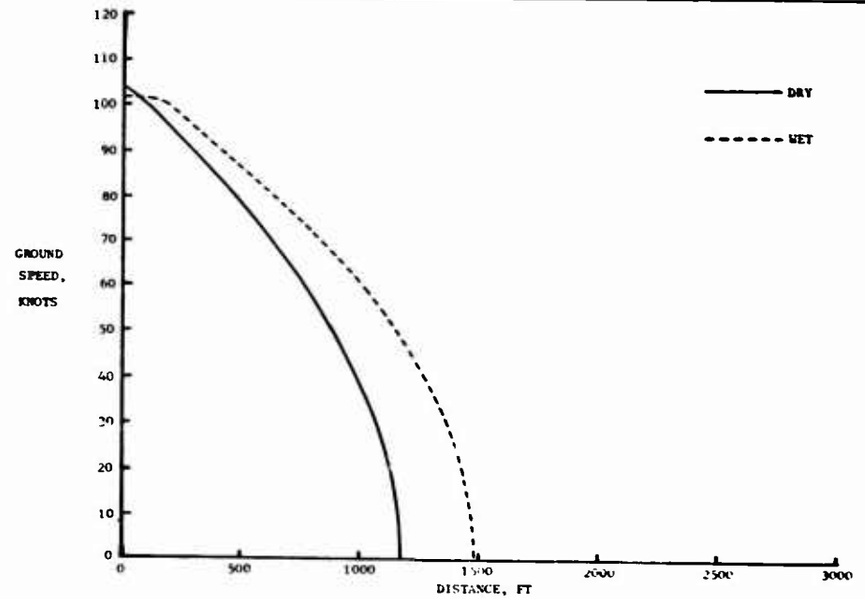


TEST SURFACE

(hh) Runway 35; NASA Wallops Station.

Figure A1.- Continued.

FARNBOROUGH RAFB, ENGLAND				RUNWAY 0/18					DATE 7-16-69							
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	AIRCRAFT		[illegible]	AIRCRAFT		[illegible]	
										REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
36	POROUS ASPHALT	———	DRY	240	10	86	29.78	180	187,900	1040	1080	346	1.17	1.20	1.05	26
			WET (.03)	240	7	86	29.78	180	185,900	1227	1300	36[illegible]				23



Test surface photograph not available.

(ii) Runway 36; Farnborough Royal Air Force Base.

Figure A1.- Continued.

APPENDIX A

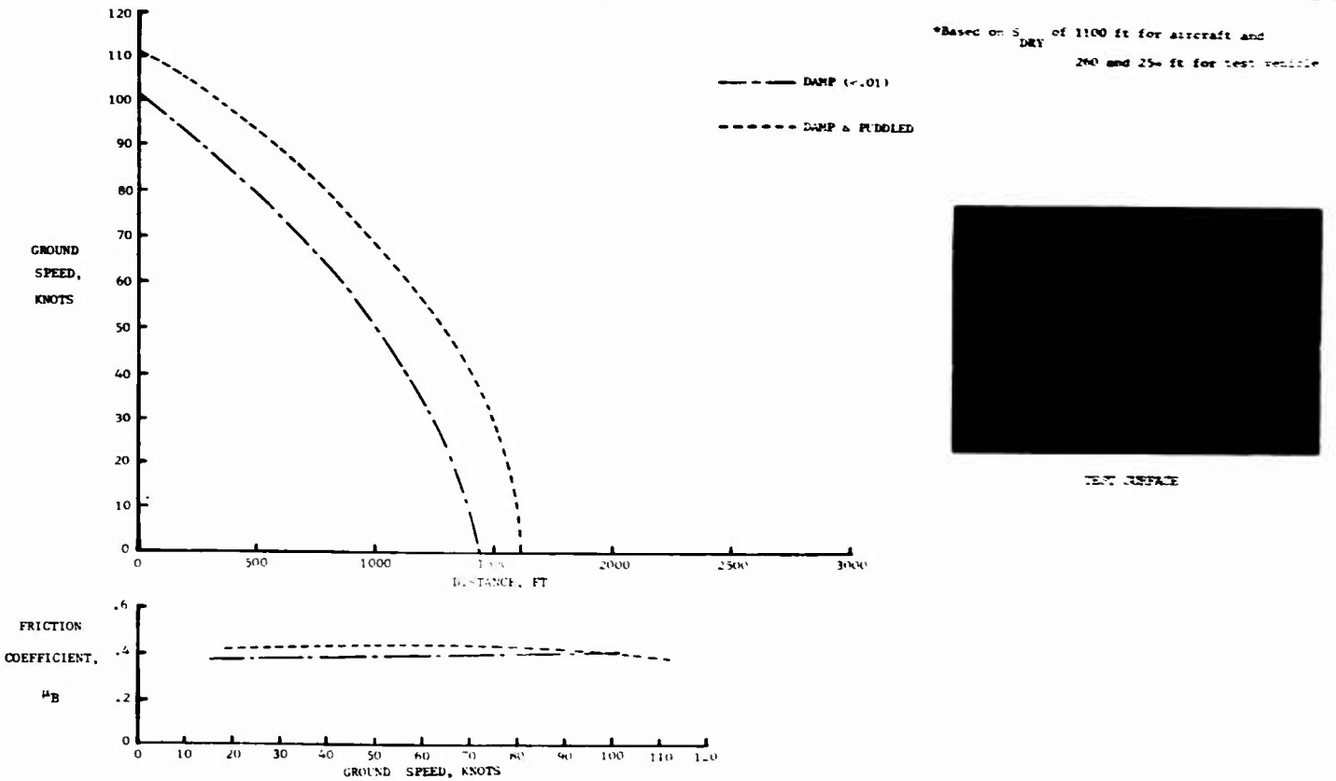


(ii) Concluded.

Figure A1.- Continued.

SHEMYA AFB, ALASKA RUNWAY 10/28								DATE 2-16-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
37	BASALT ASPHALT	—	DAMP(< .01)	0	14	36	28.92	280	192,000	1262	1270	370	1.14*	1.15*	1.42*	22
			DAMP & PUDDLED	350	9	32	28.92	280	196,000	1200	1290	3[illegible]	1.0**	1.1[illegible]*	1.4**	23

*Based on S_{DRY} of 1100 ft for aircraft and 260 and 25[illegible] ft for test vehicle



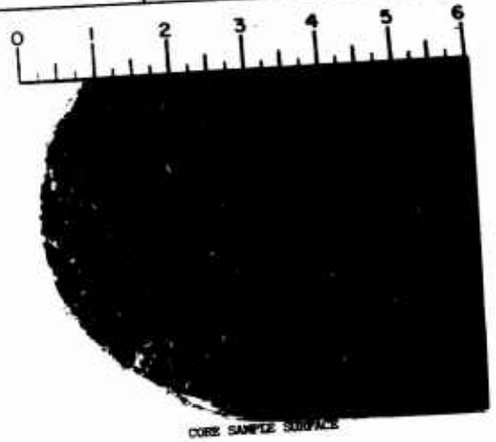
(jj) Runway 37; Shemya Air Force Base.

Figure A1.- Continued.

SHEMYA AFB, ALASKA RUNWAY: 10/28 DATE: [illegible]

SUMMARY OF PAVEMENT TRACTION FACTORS BASED ON CORE SAMPLE ANALYSIS

PAVEMENT TYPE	PREDOMINANT CHARACTERISTICS	FACTORS	CLASSIFICATION FOR WET OPERATIONS
Asphaltic Concrete	Good surface drainage. Exposed particles of degraded aggregate and some cavitation resulting from aggregate degradation. Coarse grained texture.	The surface texture characteristics of the sample of asphaltic concrete pavement from Shemya AFB are described as follows: (1) The medium to coarse grained surface texture is attributed to intraparticle fracturing and spalling of the exposed aggregate. (2) There is very little particle angularity extending above the matrix. (3) The depressions resulting from aggregate spalling provide a limited amount of surface drainage. The structural characteristics at a depth of 1-1/2 in. below the surface are described as follows: (1) The coarse aggregate skeleton consists of fractured particles of igneous rock well graded from 1/8 to 3/4 in. in diameter. (2) Some evidence of aggregate fracturing which may be attributed to overrolling or freeze/thaw damage. (3) The dense graded mix offers no subsurface drainage.	Medium Good



CORE SAMPLE SURFACE

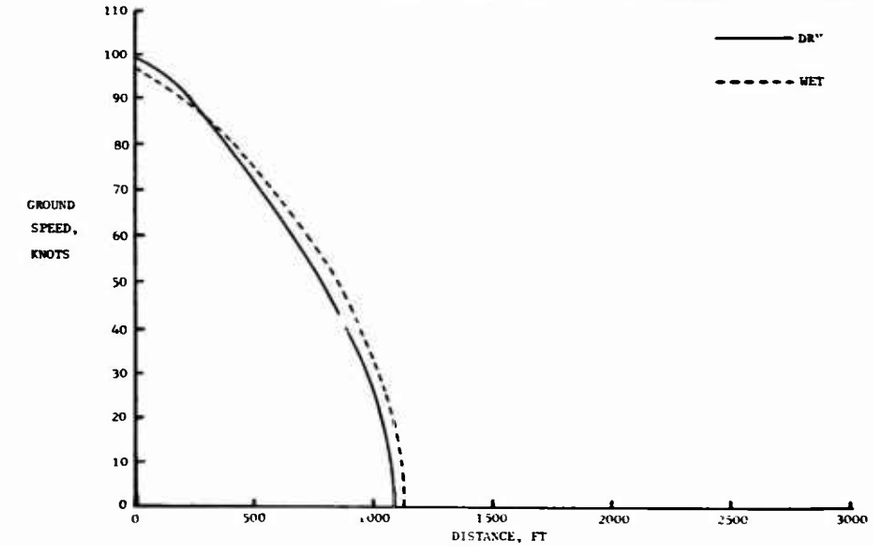


CORE SAMPLE SURFACE PROFILE

(jj) Concluded.

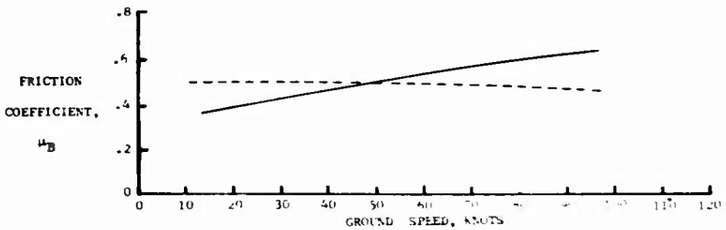
Figure A1.- Continued.

MARHAM RAFB, ENGLAND				RUNWAY 6/24					DATE 7-22-69							
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	AIRCRAFT REVOLUTION COUNTER	AIRCRAFT ACCELERATION-TIME	TEST VEHICLE REVOLUTION COUNTER	AIRCRAFT REVOLUTION COUNTER	AIRCRAFT ACCELERATION-TIME	TEST VEHICLE REVOLUTION COUNTER	
38	POROUS ASPHALT	1.073	DRY	220	5	58	30.04	240	199,900	1005	1030	366	1.07	1.17	1.10	23
			WET (.02)	210	7	59	30.04	240	194,400	1073	1200	404				23





TEST SURFACE



(kk) Runway 38; Marham Royal Air Force Base.

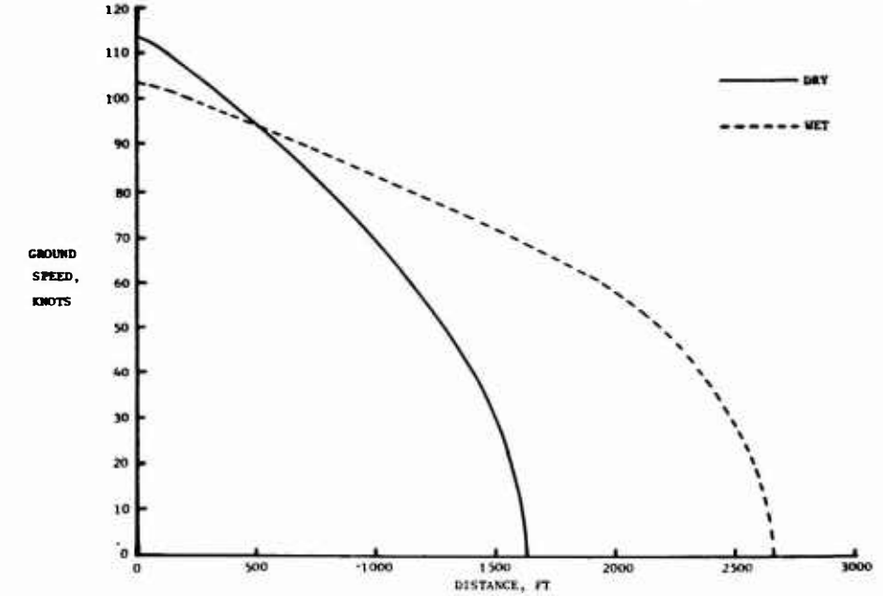
Figure A1.- Continued.

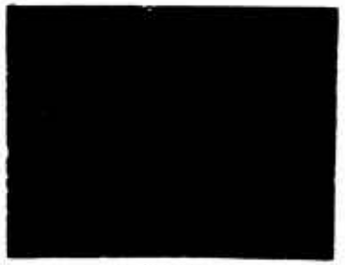


(kk) Concluded.

Figure A1.- Continued.

DYESS AFB, TEXAS				RUNWAY 16/34					DATE 6-25-69							
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
										REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
40	LANDING MATS	0.085	DRY	140	4	73	29.89	340	187,900	1119	1250	295	2.11	1.99	1.66	23
			WET (.02)	140	4	74	29.89	340	182,600	2365	2490	489				23





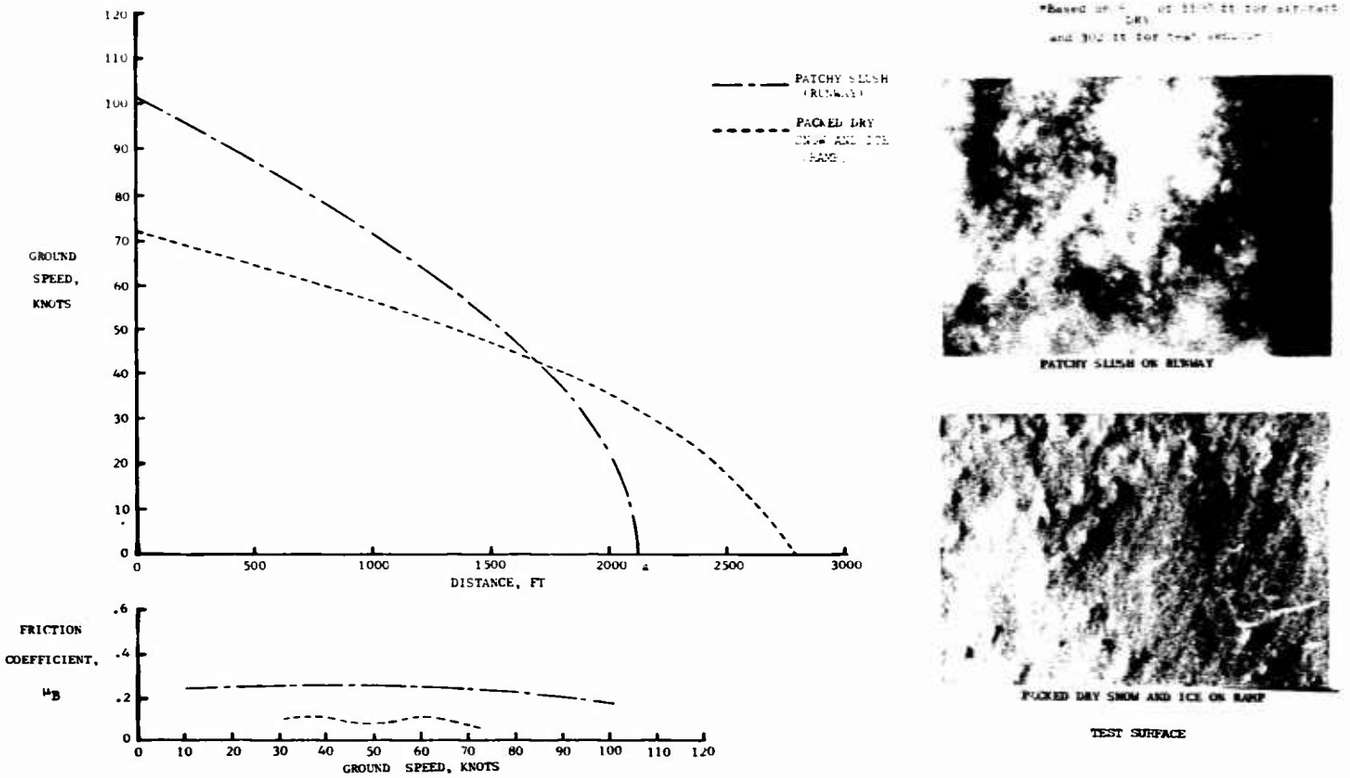
TEST SURFACE

(11) Runway 40; Dyess Air Force Base.

Figure A1.- Continued.

MALMSTROM AFB, MONTANA	RUNWAY 27/20 & RAMP						DATE 2-18-70 & 2-19-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	AVG
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
49	ASPHALT (R/W)	—	PATCHY SLUSH (0.1)	220	10	33	30.12	200	195,000	1765	2090	---	1.61*	1.90*	1.52*	1.-
41	CONCRETE (RAMP)	—	PACKED DRY SNOW AND ICE	200	10	27	30.05	020	221,800	3930	4230	1.55	3.57*	3.84*	1.41*	-

*Based on [illegible] of 31.5 ft for aircraft DRY and 302 ft for test vehicle



(mm) Runways 49 and 41; Malmstrom Air Force Base.

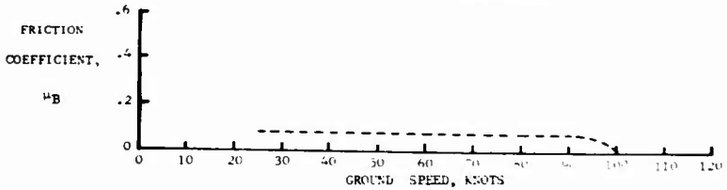
Figure A1.- Continued.

LORING AFB, MAINE			RUNWAY 1/19				DATE 1-30-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRCRAFT	TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
42	SLURRY SEAL	——	GLAZED ICE AND SNOW	330	8	21	29.65	010	198,000	3610	4120	1027	3.28*	3.75*	3.50*	*

*Based on S_{DRY} of 1100 ft for aircraft and 302 ft for test vehicle



TEST SURFACE

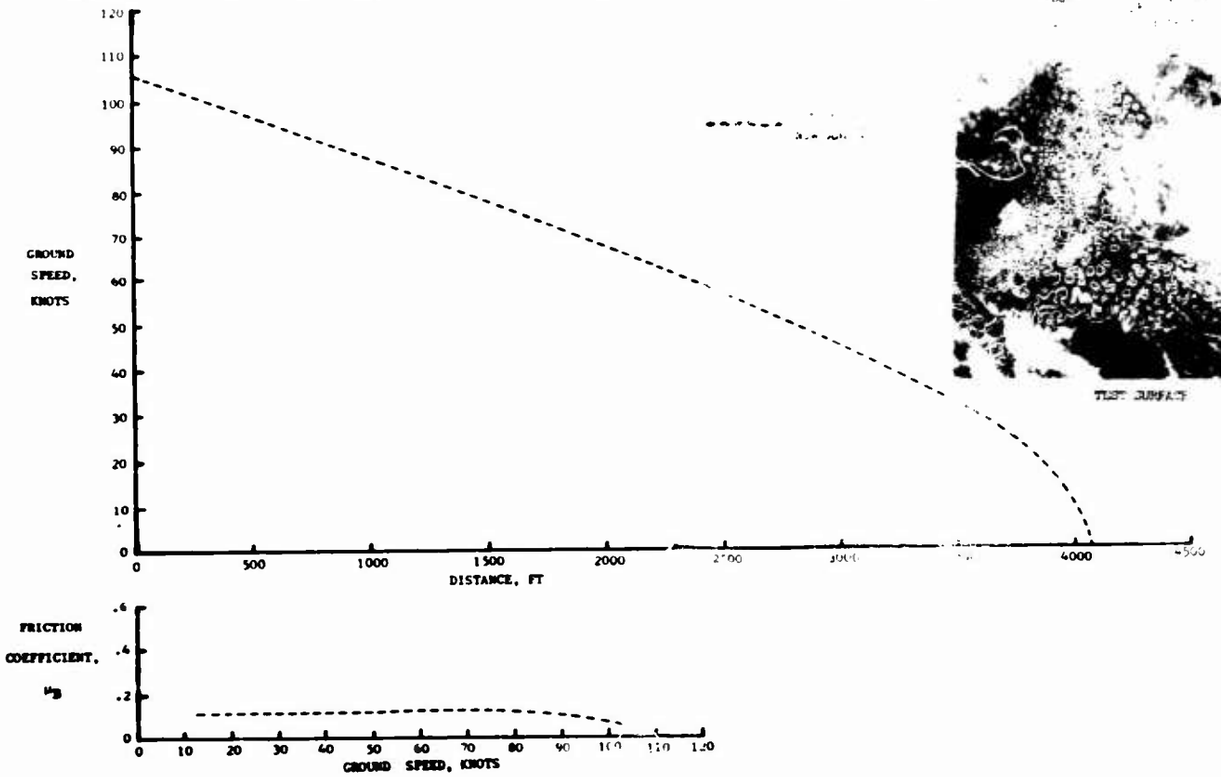


(nn) Runway 42; Loring Air Force Base.

Figure A1.- Continued.

WURTSMITH AFB, MICHIGAN	RUNWAY [illegible]	DATE [illegible]	[illegible]	[illegible]

R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP °F	ALT. SET., in. Hg	AIRCRAFT		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb									
43	CONCRETE	—	PACKED SNOW AS [illegible]	0	15	23	29.[illegible]	040	[illegible],000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



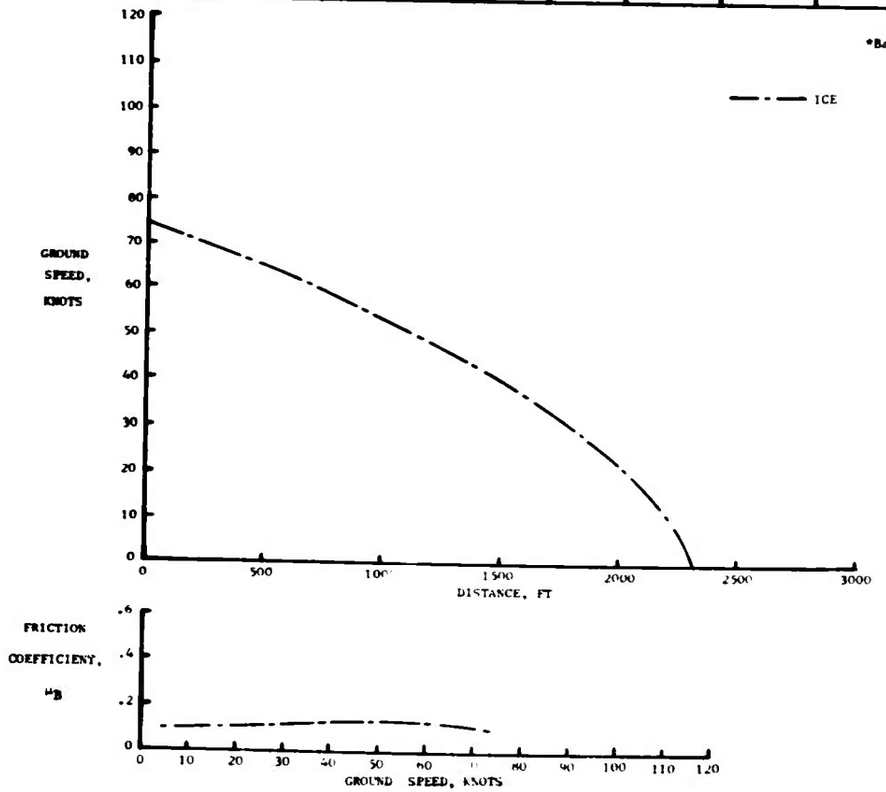
TEST SURFACE

(oo) Runway 43; Wurtsmith Air Force Base.

Figure A1.- Continued.

GRISSOM AFB, INDIANA			TAXIWAY 4/22				DATE 2-10-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL, knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
44	ASPHALT	—	SOLID ICE & SNOW	280	8	22	29.89	220	200,000	—	3520	1190	—	3.20*	3.95*	5

*Based on S_{DRY} of 1100 ft for aircraft and 302 ft for test vehicle





OVERALL VIEW



CLOSE-UP

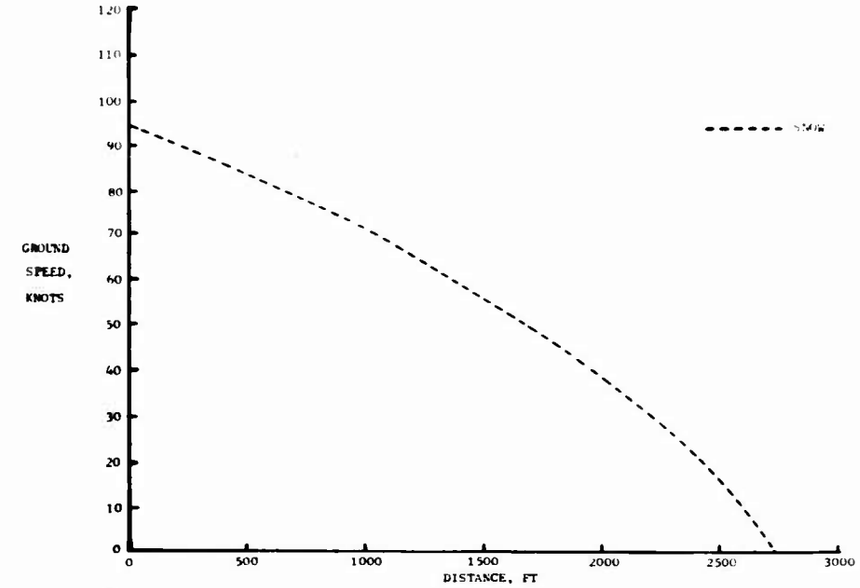
TEST SURFACE

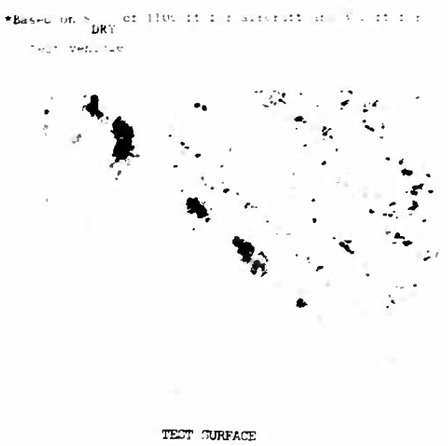
(pp) Runway 44; Grissom Air Force Base.

Figure A1.- Continued.

WRIGHT-PATTERSON AFB, OHIO	RUNWAY 5R/23L	DATE [illegible]	[illegible]	[illegible]

R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT		AIRPORT			[illegible]			[illegible]
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION TIME	[illegible] COUNTER	REVOLUTION COUNTER	ACCELERATION TIME	[illegible]	[illegible]
45	CONCRETE	—	DRY PACKED SNOW WITH ICE	320	5	8	29.91	230	207,700	3160	2030	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]





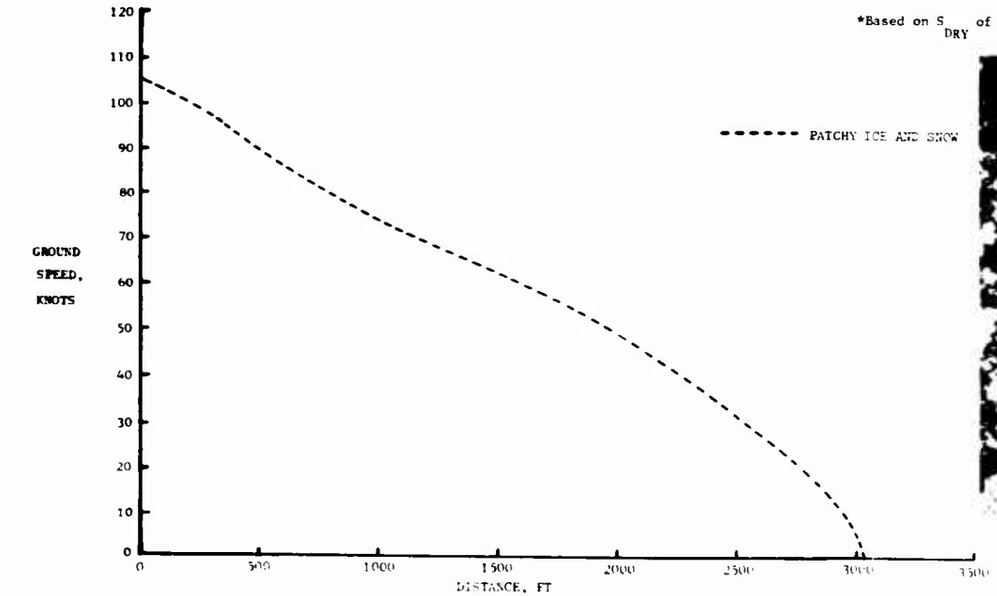
*Based on [illegible] of 110 [illegible]

(qq) Runway 45; Wright-Patterson Air Force Base.

Figure A1.- Continued.

GLENVIEW NAS, ILLINOIS RUNWAY 17/35							DATE 2-11-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. H_g	AIRCRAFT	AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
46	CONCRETE & ASPHALT	—	PATCHY ICE AND SNOW	310	9	27	29.98	350	199,000	2425	2840	758	2.20*	2.58*	2.51*	—

*Based on S_{DRY} of 1100 ft for aircraft and 302 ft for test vehicle



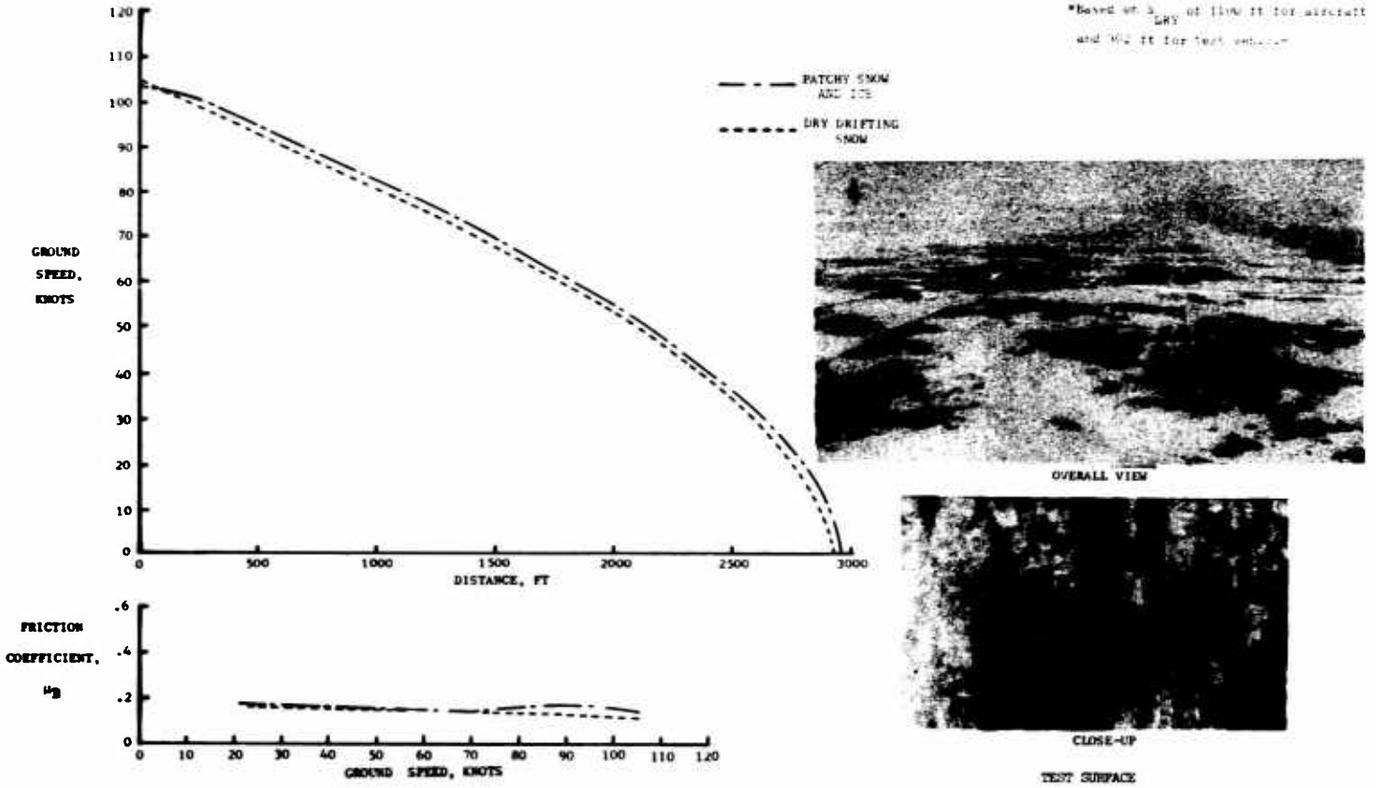


(rr) Runway 46; Glenview Naval Air Station.

Figure A1.- Continued.

K. I. SAWYER AFB, MICHIGAN			RUNWAY 1/19			DATE 1-29-70 & 2-10-70			STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
47	SLURRY SEAL	—	PATCHY SNOW AND ICE	330	13	11	29.93	010	195,000	2300	2690	493	2.09*	2.45*	1.[illegible]*	—
			DRY DRIFTING SNOW	0	18	23	29.90	010	201,000	2220	2730	685	2.02*	2.[illegible]**	[illegible]*	[illegible]

*Based on μ_{DRY} of [illegible] ft for aircraft and [illegible] ft for test vehicle

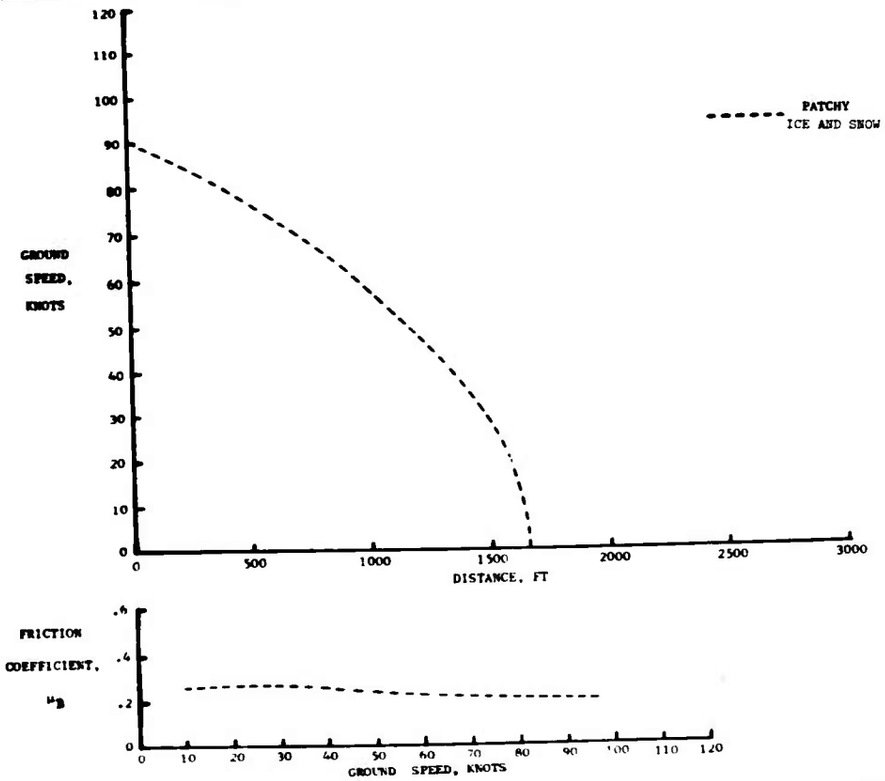


(ss) Runway 47; K. I. Sawyer Air Force Base.

Figure A1.- Continued.

McGUIRE AFB, NEW JERSEY			RUNWAY 18/36				DATE 2-4-70		STOPPING DISTANCE, FT			STOPPING DISTANCE RATIO			RCR
R/W REF. NO.	PAVEMENT SURFACE			WIND		TEMP., °F	ALT. SET., in. Hg	AIRCRAFT	AIRCRAFT		TEST VEHICLE	AIRCRAFT		TEST VEHICLE	
	MATERIAL	TEXTURE DEPTH, mm	CONDITION (WATER DEPTH), in.	DIR.	VEL., knots			HEADING	GROSS WEIGHT, lb	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	REVOLUTION COUNTER	ACCELERATION-TIME	REVOLUTION COUNTER	
48	ASPHALT	——	PATCHY ICE AND SNOW	330	23	14	30.18	360	197,200	1975	2060	656	1.80*	1.87*	2.17*	9.5

*Based on S_{DRY} of 1100 ft for aircraft and 302 ft for test vehicle



Test surface photograph not available.

(tt) Runway 48; McGuire Air Force Base.

Figure A1.- Concluded.

APPENDIX B

COMPUTATION OF TEST DATA

Aircraft Data Reduction

Accelerometer data obtained onboard the aircraft during the braking tests were reduced by use of a high-speed digital computer to provide time histories of braking distance, friction coefficient, and ground speed. Stopping distance and initial ground speed, $V_{G,O}$, were determined in an alternate manner by utilizing a calibrated nosewheel counter. Corrected stopping distances were then obtained from the appropriate accelerometer time history by either extrapolation or interpolation to $V_{G,O} = 100$ knots and extrapolation to $V_{final} = 0$ knots since the brakes were released prior to achieving a full stop; that is,

$$D_{corr} = D + \Delta D_B + \Delta D_{final} \tag{B1}$$

where

D uncorrected stopping distance from time history

ΔD_B incremental distance above or below $V_{G,O} = 100$ knots where brake engagement occurred, that is,

$$\Delta D_B = \frac{(168.9)^2 - V_{G,B}^2}{-2\bar{a}_{x,B}} \tag{B2}$$

ΔD_{final} incremental distance from brake release to $V_G = 0$, or

$$\Delta D_{final} = \frac{V_{G,final}^2}{-2\bar{a}_{x,final}} \tag{B3}$$

Calculations of braking friction coefficient, velocity, and distance time histories were made.

The braking friction coefficient equation

$$\mu_B = \frac{W}{gF_{z,m}}\left[\frac{T_n}{W}\cos(\alpha + \epsilon) - \bar{a}_x - \frac{C_D q}{W/S}\right] \tag{B4}$$

incorporates the effects of antiskid performance, aerodynamic lift and drag as measured by the accelerometer and removes the effects of idle thrust where μ_B is referred to the main-gear vertical load $F_{z,m}$; that is,

$$F_{z,m} = W\left[\left(1 - \frac{C_L q}{W/S}\right)\left(1 - \frac{\Delta x_g}{\Delta x}\right) + \frac{h_{cg}}{\Delta x}\left(\frac{C_D q}{W/S} - \frac{T_n}{W} + \frac{\bar{a}_x}{g}\right) + \frac{C_{m,g} q \bar{c}}{\Delta x (W/S)}\right]$$

Longitudinal acceleration is determined and corrected for attitude changes:

$$\bar{a}_x = a_x - g \sin(\alpha - \alpha_o) = (a_{x,RDG} - a_{x,Zero}) K_{a,x} - g \sin(\alpha - \alpha_o)$$

T_n is the installed idle thrust obtained from manufacturers' data as a function of airspeed and ambient conditions and $C_{m,g} = 0.072$ (take-off flaps, spoilers deployed). The ground speed time history was obtained from

$$V_G = V_{G,o} + \int_0^t \bar{a}_x \, dt \tag{B5}$$

wherein $V_{G,o}$ was determined from an average of the eight main-gear wheel velocities prior to brake engagement. Distance time histories were then obtained by integration as

$$D = \int_0^t V_G \, dt \tag{B6}$$

A value for three-point aerodynamic drag coefficient was obtained from unbraked tare runs over the test speed range by using

$$C_D = \mu_R C_L - \frac{W/S}{q}\left\{\frac{\bar{a}_x}{g} - \frac{T_n}{W}\cos(\alpha + \epsilon) + \mu_R\left[1 - \frac{T_n}{W}\sin(\alpha + \epsilon)\right] - \sin(\alpha - \alpha_o)\right\} \tag{B7}$$

where

$\mu_R = 0.015$ (assumed)

$C_L = 0.310$ (manufacturers' value with take-off flaps and spoilers deployed)

$\epsilon = 0^o$ (thrust misalinement angle)

T_n manufacturers' installed idle thrust value for velocities and ambient conditions of tare run

APPENDIX B

Auxiliary equations used in the reduction of accelerometer data were as follows:

$$V_A = V_G + V_w \tag{B8}$$

$$q = 0.0002916 \frac{p_a}{T_a} V_A^2 \tag{B9}$$

A three-view drawing of the test aircraft with its pertinent geometric characteristics is shown in figure B1.

Although it is felt that the inclusion of runway slope data in the present computations of friction coefficients, stopping distance, and the overall rating of runways with regard to slipperiness would have been desirable, insufficient civil engineering data were available to incorporate this correction to the present data; that is, only average runway slope data are available for specific runways, wherein, several varying slopes were observed within a region covered by the full-stop tests of the present investigation. Also, ambient corrections to provide stopping distances for each runway at sea level under standard dry conditions were not made since it is generally felt that these corrections would be well within the accuracy of the present data.

The alternate method for determining aircraft stopping distance and initial velocity, as previously mentioned, utilized a nose wheel counter calibrated to measure ground speed at brake engagement and also braking distance. The latter braking distance data were corrected to a brake engagement speed of 100 knots by

$$D_{corr} = \frac{(168.9)^2}{V_{G,B}^2} D \tag{B10}$$

where

$V_{G,B}$ ground speed at brake engagement as determined from calibrated nose wheel counter, ft/sec

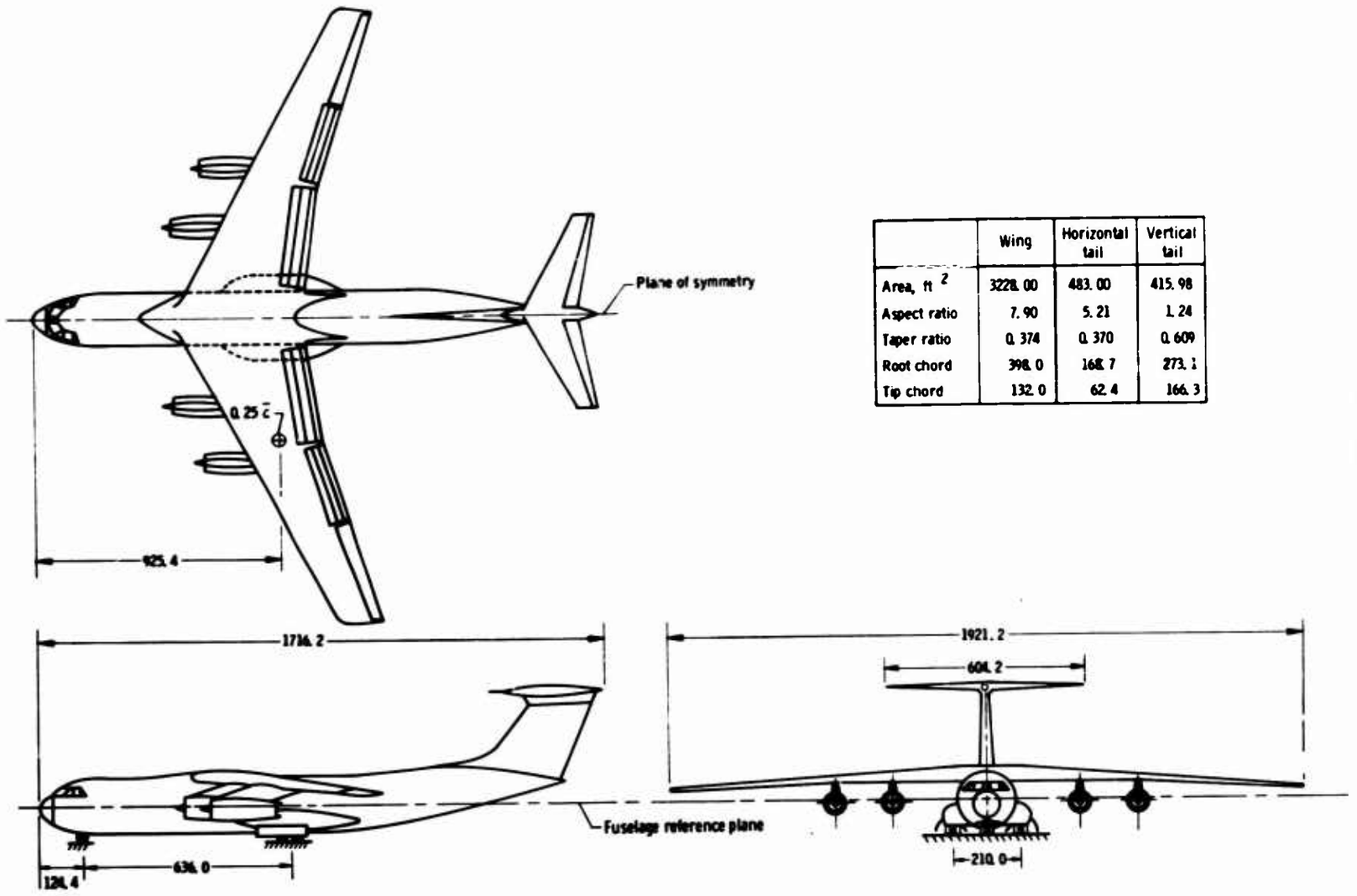
D uncorrected counter braking distance, ft

NASA Diagonal-Braked Test Vehicle Data Reduction

Stopping distance data obtained from the test vehicle counter mounted on the fifth wheel were corrected in a manner similar to those obtained from the aircraft instrumented nose wheel; that is,

$$D_{corr} = \frac{(88)^2}{V_{G,B}^2} D \qquad \text{(B11)}$$

wherein the test vehicle data were corrected to a brake engagement speed of 60 mph and D is the uncorrected braking distance for the test vehicle.



	Wing	Horizontal tail	Vertical tail
Area, ft^2	3228.00	483.00	415.98
Aspect ratio	7.90	5.21	1.24
Taper ratio	0.374	0.370	0.609
Root chord	398.0	168.7	273.1
Tip chord	132.0	62.4	166.3

Figure B1.- Three-view drawing of C-141A test aircraft. All dimensions are in inches unless otherwise specified.

APPENDIX C

CIVIL ENGINEERING DESCRIPTIONS OF RUNWAYS TESTED

This appendix presents the civil engineering descriptions of the runways that were supplied by the specific Airport or Air Force Base. Such data were not available for the following:

Runway	Location
2	England AFB, Louisiana
3	Marham RAFB, England
14	Chicago Midway Airport, Illinois
17	Mildenhall USAFE, England
21	Myrtle Beach AFB, South Carolina
23	Otis AFB, Massachusetts
24	Aviano USAFE, Italy
25	Alconbury USAFE, England
28	Pope AFB, North Carolina
33	Dover AFB, Delaware
35	NASA Wallops Station, Virginia
37	Shemya AFB, Alaska
39	Meigs Airport, Illinois
40	Dyess AFB, Texas
41	Malmstrom AFB, Montana
42	Loring AFB, Maine
43	Wurtsmith AFB, Michigan
44	Grissom AFB, Indiana
45	Wright-Patterson AFB, Ohio
46	Glenview NAS, Illinois
47	K. I. Sawyer AFB, Michigan
48	McGuire AFB, New Jersey
49	Malmstrom AFB, Montana

Data for runways 4 and 15, 10 and 11, and 26 and 36 have been combined.

References in the civil engineering descriptions of the British runways are to items included in the British Ministry of Public Building and Works Airfield Specifications.

APPENDIX C

DYESS AFB, TEXAS – RUNWAY 1

Test runway: 16/34 Length, 13 500 ft Width, 300 ft	Landing approach 34
Construction in 1953	11 700 ft PCC south end, first 1000 ft by 300 ft, rigid 16 in. thick. From north end, first 650 ft, 19 in. thick; next 500 ft, 10 in. thick; next 2300 ft, 15 in. thick. Interior keel, 18 in. thick.
	Surface treatment, rigid nonskid (belt finished). All emulsified asphalt; slurry surface treatment.
	Characteristics of large aggregate: PCC; 2 in. maximum crushed limestone and angular gravel; bituminous, 3/4 in. maximum size.
Construction in 1955	Additional 2300 ft (north extension)
Construction in 1964	Runway widened to 300 ft and 75 ft, interior keel (belted).
Construction in 1965 and 1967	Asphalt runway given slurry surface treatment. Cost less than $0.10 per square yard.
Transverse slope	$1\frac{1}{2}\%$
Longitudinal grade	Varies from 0 to 0.3%
Precipitation	Rain – 22.55 in. Snow – 3.60 in. Highest month – May (3.68 in.) Lowest month – January (0.88 in.)
Drainage	Adequate
Pavement conditions	Good. Some patching needed occasionally on north 3000 ft.

APPENDIX C

OFFUTT AIR FORCE BASE, NEBRASKA – RUNWAYS 4 and 15

Test runway: 12/30 Length, 10 000 ft Width, 300 ft	Landing approach 30
Construction in 1941	Station 0 + 00 to station 57 + 00
Construction in 1954	Station 57 + 00 to station 100 + 00
Construction in 1956	Reconstructed station 0 + 00 to station 57 + 00.
Construction in 1969	Grooved 145 000 sq yd of runway with 1/4 in. by 1/4 in. grooves on 1¼ in. centers at a cost of $133 467.
Longitudinal grade	0 + 00 to 20 + 50 -0.985% 20 + 00 to 38 + 00 -0.320% 38 + 00 to 55 + 00 -0.958% 55 + 00 to 80 + 00 -1.00% 80 + 00 to 100 + 00 -0.00%
Precipitation	Rain – 27.85 in. Snow – 27.90 in. Highest rain month – June (4.64 in.) Lowest rain month – January (0.72 in.) Highest snow month – February (6.6 in.) Lowest snow month – May (0.1 in.)
Drainage	Good
Pavement condition	Good. Minor repair of spalling and joint seal each year.

APPENDIX C

ELLINGTON AFB, TEXAS – RUNWAY 5

Test runway: 04/22 Length, 6800 ft Width, 150 ft	Landing approach 04
Construction in 1941	Original 5000 ft runway consisted of 10 to 11 in. of PCC with a burlap drag finish and aggregate from Eagle Lake $1\frac{1}{2}$ in. maximum grain size, very sound and hard.
Construction in 1956	Runway extended on the 04 end consisted of 10 to 11 in. of PCC for 1800 ft with burlap drag finish and aggregate from Eagle Lake $1\frac{1}{2}$ in. maximum grain size, very sound and hard. Also overlayed 2388 ft of 22 end.
Longitudinal grade	0 + 00 to 50 + 00 + 0.6% 50 + 00 to 68 + 00 - 0.6%
Transverse slope	Crowned with 1.5% slope
Precipitation	Annual precipitation – 44.9 in. Annual snowfall – 0.5 in. Highest month – July (4.84 in.) Lowest month – March (2.00 in.)
Drainage	Good; very little puddling.
Pavement condition	Very good to excellent

APPENDIX C

EDWARDS AFB, CALIFORNIA – RUNWAY 6

Test runway: 04/22 Length, 16 800 ft Width, 300 ft	Landing approach 22
Construction history	17 in. thick PCC within test section.
	Surface finish, belt finished PCC, 5.33 sack mix with W/C = 5.0.
	Characteristics of large aggregate: 3 in. maximum size to sand, well-graded and sound. 36.9% loss in Los Angeles abrasion test. Total cost of paving and surface $6 578 000.
	Not much rubber buildup and no removal projects to date.
Transverse slope	Crowned with 0.5% slope
Longitudinal grade	0.140% through test section
Precipitation	Annual precipitation – 8.77 in. Annual snowfall – Trace. Highest month – December (0.95 in.). Lowest month – June and July (0.00 in.).
Drainage	Very effective, no problems
Pavement condition	Good. Has multiple hairline cracks on surface; some oxidation of iron in aggregate; no obvious full-depth cracking.

APPENDIX C

WRIGHT-PATTERSON AFB, OHIO – RUNWAY 7

Test runway: 05L/23R Length, 12 600 ft Width, 300 ft	Landing approach 05L
Construction in 1946	300 ft by 10 000 ft of 21 in. reinforced PCC, burlap drag finish, large aggregate 4 in. maximum from local pits.
Construction in 1956	1000 ft extension on southwest end of 21 in. reinforced PCC, burlap drag finish, large aggregate $1\frac{1}{2}$ in. maximum from local pits.
Construction in 1959	1600 ft extension on southwest end of reinforced PCC; thickness varies with 13 in. on edges and 15 in., 18 in., and 19 in. center portions; burlap drag finish, large aggregate $1\frac{1}{2}$ in. maximum from local pits.
Construction in 1964	Repair of original 10 000 ft; consisting of deteriorated joint and popout repairs with PCC, using quality type 3/4 in. maximum size crushed aggregate, at total cost of $1 116 000 including the architectural engineer inspection and testing. Grinding the center 50 ft width for 2831 linear feet in seven areas between sta. 73 + 85 and sta. 113 + 84 for a toual area of 154 241 square feet, costing $125 684.35 at a unit cost of $0.845 per square foot. The finish transverse grooves were cut 1/16 in. deep, 3/16 in. wide, and spaced 3/4 in. center to center.
Construction in 1969	Removed rubber from approximately 80 000 sq yd of pavement on 23R at center line crown, except approximately 1800 ft of warped area at taxiway 12, where crown was eliminated.
Longitudinal grade	Beginning at 05L end, 0.00% from sta. 0 + 85.54 to approximately station 41 + 00, +0.36% from approximately sta. 41 + 00 to sta. 81 + 00, +0.10% from sta. 81 + 00 to sta. 126 + 85.54 end of 23R. Test was entirely in the +0.36% grade.

APPENDIX C

WRIGHT-PATTERSON AFB, OHIO – RUNWAY 7 – Concluded

Precipitation	**Annual precipitation, 35.9 in.** **Annual snowfall, 26.6 in.** **Highest month – June (4.3 in.)** **Lowest month – October (2.0 in.).**
Drainage	**Good, except flat warped area at taxiway 12.**
Pavement condition	**Fair. Predominant defects are deterioration under and behind the repaired areas, surface sealing, and spalling along joints.**

APPENDIX C

LOCKBOURNE AFB, OHIO – RUNWAY 8

Test runway: 23L/05R
Length, 12 100 ft
Width, 200 ft

Landing approach 23L

Construction in 1960

Center 150 ft, 16 in. PCC, 29 in. gravel base. Outer lanes, 25 ft each, 14 in. PCC, 29 in. gravel base.

Surface, broom finish.

Large aggregate – crushed gravel, maximum size 2 in.

Sieve size, U.S. standard square mesh	Percent by weight passing individual sieves	
	No. 4 to 1 in.	1 in. to 2 in.
$2\frac{1}{2}$ in.	---------	100
2 in.	---------	95 to 100
$1\frac{1}{2}$ in.	100	35 to 70
1 in.	95 to 100	0 to 15
1/2 in.	25 to 60	0 to 5
No. 4	0 to 10	
No. 8	0 to 5	

Transverse slope

1% from center line

Longitudinal grade

0.04%

Precipitation

Rain annual – 36.1 in.
Highest month – July (4.3 in.)
Lowest month – October (1.7 in.)
Snow annual – 24.8 in.
Highest month – January (6.3 in.)
Lowest month – May (0.1 in.)

Drainage

Turf side slopes extend approximately 200 in. at 3%. Some puddling in low spots.

Pavement conditions

Excellent, with minor surface popouts. Very little cracking.

APPENDIX C

LANGLEY AFB, VIRGINIA – RUNWAY 9

Test runway: 07/25 **Length, 10 000 ft** **Width, 150 ft**	**Landing approach 07**
Construction in 1940 and 1941 and extension in 1943	**8 in., -6 in., -8 in. PCC.**
Construction in 1944	**Overlayed with 8 in. PCC, burlap drag finish.** **Large aggregate: Graded with 35% crushed granite from Richmond, Virginia area.** **During the past 10 years, slabs have been replaced extensively on the runway ends. No slab replacement observed in test area (interior of the runway). Rubber deposits have not been removed.**
Transverse slope	**1%**
Longitudinal grades	**07 end 0 + 00 — 0% (level)** **10 + 00 — 0.08% down** **20 + 00 — 0.14% up** **30 + 00 — 0.07% up** **40 + 00 — 0.01% up** **50 + 00 — 0.06% down** **60 + 00 — 0.08% down** **70 + 00 — 0.14% up** **75 + 00 — 0.10% up** **80 + 00 — 0.07% down** **90 + 00 — 0.16% down** **95 + 00 — 0.08% down** **25 end 100 + 00**
Precipitation	**Annual precipitation – 40.25 in.** **Snowfall – 5.85 in.** **Highest month – July (4.91 in.)** **Lowest month – October (2.25 in.)**
Drainage	**Good; no ponding observed.**
Pavement condition	**Numerous slabs repaired with epoxy patches (mostly corner spalls).**

APPENDIX C

YEOVILTON RNB, ENGLAND – RUNWAYS 10 AND 11

Test runway – 09/27
Surface – Wire brush texture
Main construction – 8 in. PQ concrete
Date of construction – August 1967

Surface of runways (excluding runway ends): Except for the areas indicated at each runway end, the concrete is to be roughened by drawing a purpose-made wire broom across the pavement at right angles to the side forms, after the finishing operations, but while the concrete is still soft enough to take an impression. The broomhead is to be wire filled, of 24 in. minimum width, with 32 gage by 1/20 in. wire tapes. The contractor is to roughen trial bays for approval of the surface texture by the Specification Officer (S.O.), and thereafter is to reproduce a uniform texture throughout the runway length.

Surface of runway ends and taxiways: The concrete surfacing of runway ends and taxiways is to be slightly roughened or textured. A suitable finish can be obtained by drawing a stiff broom lightly across the pavement at right angles to the side forms, after the finishing operations but while the concrete is still soft enough to take an impression.

Surfaces of concrete surfacing other than runways and taxiways, and of lower slabs of double-slab-concrete construction, and surfaces of concrete which are to receive bituminous surfacing: The surface is to receive no special treatment other than the finishing operations required to produce the specified degree of accuracy of surface level.

Scoring of concrete surfacing: The runway is to be scored transversely by a single pass of a cutting drum incorporating not less than 50 circular segmented diamond saw blades per 12 in. width of drum. The drum is to be set at 1/8 in. depth on a multiwheeled articulated frame with outrigger wheels, fixed to give a uniform depth of scoring over the entire surface of the runway, to ensure the removal of all laitance and the exposure of the aggregate. The blades are nominally 1/8 in. thick, evenly spaced with actual blade thickness of 0.110 in. and space between the blades of 0.133 in. Sawing apparatus is to include water tankers and pressure sprays.

APPENDIX C

J.F. KENNEDY AIRPORT, N.Y. – RUNWAY 12

Test runway: 4R/22L **Length 8400 ft** **Width, 150 ft**	**Landing approach 22L**
Construction in 1959	12 in. PCC burlap drag finish, Aggregate (large) 3 in. minus trap rock. Transverse slope, 1%. Longitudinal grade, 0% (level).
Runway grooved in 1967	3/8 in. width by 1/8 in. depth by $1\frac{3}{8}$ in. pitch with 5/32 in. radius groove 150 ft wide by 8400 ft long. Cost $157 490 or $0.13 per sq ft Rubber deposits removed prior to grooving but not after the grooving project.
Precipitation	Annual precipitation – 40 in. Snow – 14 in. Highest month – March Lowest month – July
Drainage	Fair. After wetting, numerous bird baths or slow draining areas were observed.
Pavement conditions	Considerable number of slabs with cracks along runway center line, and a number of longitudinal edge cracks.

APPENDIX C

SEYMOUR JOHNSON AFB, N.C. – RUNWAY 13

Test runway: 08/26 Length, 11 758 ft Width, 300 ft	Landing approach 08
Construction in 1958 and 1959	Runway extended to 300 ft in width and 11 758 ft in length, with 1000 ft PCC ends, 2100 ft rigid keel, and 7658 ft flexible interior.
Construction in 1960	75 ft flexible center removed and replaced with 17 in. PCC burlap drag finish. Large aggregate, crushed large rock (fine grained, banded, and foliated metavolcanic or silicic composition).
Construction in 1968	Grooves: 1/4 in. wide by 1/4 in. deep by $2\frac{1}{4}$ in. pitch with square grooves. Alternate grooved and ungrooved sections repeating in 2 ft transverse strips, 140 ft wide by 9758 ft long. Cost \$60 750 or \$0.04 per sq ft. Rubber deposits have not been removed since grooving.
Transverse slope	1%
Longitudinal grades	08 end 0 + 00 Not obtained 10 + 00 0.04% down 20 + 00 0.14% up 50 + 00 0.60% up 86 + 58 Not obtained 117 + 58
Precipitation	Annual precipitation – 51.7 in. Snowfall – 6 in. Highest month – July (7.2 in.) Lowest month – April (3.0 in.)
Drainage	Excellent. After wetting operations, no ponding occurred.
Pavement condition	A series of fine longitudinal cracks have developed in numerous slabs, probably because of the pavement vibrating machine used in construction.

APPENDIX C

BEALE AFB, CALIFORNIA – RUNWAY 16

Test runway: 14/32 Length, 12 000 ft Width, 300 ft	Landing approach 32
Construction in 1957 and 1958	20 in. PCC, 6 in. base, 24 in. minimum select subbase.
Construction in 1967	Runway grooved with 1/4 in. wide by 1/4 in. deep by 1 in. spacing, except where grooves are adjacent to construction joints. Groove is then 3 in. from joint. Grooved area, 140 ft by 10 800 ft (70 ft on both sides of runway center line). Original contract price for grooving $173 925 for the area 140 ft by 10 000 ft or $0.125 per sq ft. Because of an error by the contractor, $143 560 was paid for an area 140 ft by 10 800 ft or $0.095 per sq ft. Rubber removed from 14 end of runway (area 80 ft by 3000 ft) in 1967 and 1969.
Transverse slope	Crowned with 1.0% slope.
Longitudinal grade	Station 260 + 00 -0.32% Station 225 + 00 +0.20% Station 205 + 00 -0.09% Station 170 + 00 +0.09% Station 140 + 00
Precipitation	Annual precipitation – 21.5 in. Highest months – January and February (4.0 in.) Lowest months – June and September (Trace)
Drainage	Good.
Pavement condition	Excellent.

APPENDIX C

SPANGDAHLEM AIR BASE, GERMANY – RUNWAY 18

Test runway: 05/23 Length, 9974 ft Width, 150 ft	Landing approach 05
Construction in 1951	Original 8000 ft runway consisted of 8 in. of PCC. The 05 end consisted of 7 in. of PCC.
Construction in 1957 and 1958	Runway extended on the 23 end consisted of 10 in. of PCC on top of 5.5 in. of lean PCC. Overruns were also constructed (05 end, 400 ft) consisting of PSP over 4.5 in. of asphaltic concrete. An overlay was put on the runway; on the interior portion 4 in. of asphaltic concrete, and the other portions, 4 in. of AC over 5.5 in. of lean PCC.
Construction in 1967	A 4 in. asphaltic concrete wearing surface (40 ft each side of center line of runway) between stations 274.68 and 1100.8 and stations 1850.93 to 2600.93 (test conducted on this surface). A 1/8-in. slurry seal caps the pavement.
Longitudinal grades (in meters)	05 end 0 + 00 -357.53 20 + 00 -345.77 50 + 00 -348.75 90 + 00 -352.53 120 + 00 -354.03 150 + 00 -357.53 180 + 00 -360.06 220 + 00 -362.14 260 + 00 -364.09 300 + 00 -364.70
Precipitation	Annual rainfall – 25.62 in. Annual snowfall – 19.5 in. Highest month – January (6.3 in.) Lowest month – April (1.35 in.)
Drainage	Good. After wetting operations, no ponding occurred.

APPENDIX C

ELMENDORF AFB, ALASKA – RUNWAY 19

Test runway: 05/23 Length, 10 000 ft Width, 200 ft	Landing approach 05
Construction in 1941	$1\frac{1}{2}$ in. asphalt concrete surface, $2\frac{1}{2}$ in. binder, 4 in. base course, 6 in. PCC. Subbase is natural glacial gravel, which has a very high CBR rating.
	Surface finish, dense compacted asphalt concrete.
	Characteristics of large aggregate. Maximum size 3/4 in.; gravel was run through a crusher, but high percentage is rounded and smooth.
Construction in 1953 and 1957	Surface added. Plant-mix asphalt concrete, 3/4 in. maximum size crushed glacial gravel.
Transverse slope	Average slope on transverse crown is 0.75%, but there is some variation because of 1964 earthquake.
Longitudinal grade (West to east)	End to approximately 3000 ft, 0.18% To east end, 0.46%
Precipitation	Rain – 17.24 in. Snow – 71.7 in. Highest month – August (2.49 in.) Lowest month – May (0.63 in.)
Drainage	Good, no puddling.
Pavement conditions	Fair. The dense compaction coupled with the rounded, smooth aggregate makes the surface very slick. Because of the aggregate type and the extreme weather conditions, much of aggregate in surface course is exposed and some aggregate popping is evident. Pavement cracked both longitudinally and transversely in many places, partly because of the 1964 earthquake.

APPENDIX C

BITBURG AIR BASE, GERMANY – RUNWAY 20

Test runway: 06/24 Length, 8222 ft Width, 148 ft Overruns, 850 ft (24 end), 2100 ft (06 end)	Landing approach 24
Construction in 1951 and 1952 (original runway)	Subgrade – brown and gray lean clay (CL). Base course – 10 in. lavalite cinders (K = 200) covered by 2 in. sand cushion. Pavement, 8 in. of PCC (flexural strength approximately 700 psi).
Construction in 1956 and 1957	Original overruns, consisting of 8 in. of PCC (700 psi flexural strength).
Construction in 1958	Overlay of runway 800 ft from 24 end and 700 ft from 06 end consisting of 7 in. of PCC (flexural strength approximately 550 psi). Interior overlay: 4 in. of asphaltic concrete. Overlay of the overruns (300 ft on both ends) consisting of 7 in. of PCC and 4 in. of AC. Overrun extension at 24 end of 1 in. DBT (1 in. DBT on 06 overrun extension in 1964).
Construction in 1968	Overlay, 4 in. asphalt at a cost of $250,000. No seal or antiskid coat applied. The Marshall stability is 1500 lb (680 kg) at minimum; the Marshall extension factor is (1/10 mm) 18 at maximum. The interior space (cavity) limit of mineral mix is 3 to 5%. The aggregate for the surface course is between 0.063 and 18 mm. The mineral filler is between 0.063 and 0.002 mm.
Construction in 1969	The east touchdown area overlayed with $1\frac{1}{2}$ in. asphalt concrete.
Precipitation	Annual rainfall – 25.4 in. Annual snowfall – 19.4 in. Highest month – July (2.81 in.)

APPENDIX C

BITBURG AIR BASE, GERMANY – RUNWAY 20 – Concluded

Longitudinal grades (in meters)	06 end	
	30 + 00	-368.68
	60 + 00	-369.50
	90 + 00	-370.28
	120 + 00	-372.07
	150 + 00	-372.84
	180 + 00	-372.54
	1620 + 00	-372.81
	2440 + 00	-374.06
Drainage	Good. After wetting operations, no ponding occurred.	

APPENDIX C

WADDINGTON RAFB, ENGLAND – RUNWAY 22

Runway tested: 03/21
Surface, asphalt (constructed 1968)
Main construction, rolled asphalt (constructed 1968)

(NOTE: This specification is based on weather conditions in the United Kingdom. At overseas airfields some amendments may be necessary, particularly in binder requirements.)

Materials

Surface binder: The binder for spraying the surface cut back bitumen conforming with BS 3690, Grade 50 secs. It is to have the following properties when tested in accordance with BS 3255, except that distillation is to be determined in accordance with the appendix of BS 3690.

Viscosity (S.T.V.) at 40° C (140° F):	50 ± 10 (secs)
Distillation:	
(a) Distillate to 225° C (437° F) (percent by volume)	1 max.
360° C (680° F)	8 to 14
(b) Penetration of residue at 25° C	100 to 300
Solubility in carbon disulphide (percent by weight):	99.5
Ash content (percent by weight):	0.5 max

Immediately prior to the application of the hot binder, a wetting agent at the rate of $1\frac{1}{2}\%$ by weight is to be added and thoroughly mixed in accordance with the manufacturer's written instructions.

Bitumen for coating chippings: The chippings are to be coated with petroleum bitumen conforming with BS 3690, grade 200 pen.

Wetting agent: The wetting agent is to be sterine amine or equal.

Chippings: The chippings are to be single-sized, in accordance with BS 63, and are to be of rock from one of the following: basalt, gabbro, granite, gritstone, hornfels, porphyry, or quartzite. They are to be 1/8 in. nominal size conforming with the grading and particle shape given in table I of the BS.

Aggregate crushing value: A sample of proposed chipping but of a size passing a 1/2 in. but retained on a 3/8 in. BS sieve is to be tested in accordance with BS 812 to determine its aggregate crushing value; the value must be less than 16.

Coated chippings: The chippings are to be dried in an approved rock dryer, heated to a temperature of 240° to 280° F (116° to 138° C), and then coated in an approved mixer with bitumen at a rate of 3/4 to 1½% by weight at a temperature of 300° to 350° F (149° to 177° C).

Stripping test: A stripping test is to be carried out on the selected chippings as follows:

(a) After heating, take a sample from the dryer, coat with bitumen at a temperature of 320° F (160° C) at the rate specified above, and thoroughly mix.

(b) Transfer to a 1-quart screw-cap glass jar to not more than 1/2 capacity, then completely cover with distilled water.

(c) Fasten the screw-cap tightly and let stand for a period of 24 hours, then examine for stripping of the bitumen.

(d) If stripping has occurred, reject the chippings.

Plant

Heater and distributor for surface binder: The heated binder is to be applied by a mobile combined heater and distributor with pressure feed, all complying with BS 1707. When the test set out in the BS is carried out, the deviation of binder delivered on each 2 in. strip is not to be greater than 15% from the mean for all the 2 in. units over the effective width. Furthermore, the mean of the amount of binder collected in any three adjacent trays within the effective width is not to differ from the average by more than 10%. A certificate to this effect, not more than 1 month old from an independent laboratory is to be submitted to the S.O. in regard to each heater and distributor prior to its use.

Mechanical gritter: The heated and coat chippings are to be distributed by a mechanical gritter of approved type incorporating a mechanical feed capable of ensuring that the selected rate of spread is rigidly maintained.

Rollers: Not less than three multiwheeled, smooth-tread, rubber-tyred rollers, each loaded to at least 6 tons, are to be used in conjunction with each distributor. They may be either self-propelled or towed by smooth-tread rubber-tyred tractors.

Workmanship

Restrictions during bad weather:

(a) No work is to be carried out during periods of rain, snow, or sleet; on frozen surfaces or where water is lying.

(b) When in the opinion of the S.O., weather conditions make it necessary, suitable protection is to be afforded to the heated and coated chippings during delivery.

APPENDIX C

WADDINGTON RAFB, ENGLAND – RUNWAY 22 – Concluded

Pit covers, gully gratings, and airfield markings: Existing pit covers, light fittings, and gully gratings are to be protected by masking or other means, and the surface dressing is to be finished neatly thereto. When masking of the airfield markings by similar means is not indicated, they may be obliterated and are not to be reinstated by the contractor.

Preparation of the existing surface: Immediately before spraying the binder, the existing surface is to be cleaned thoroughly by mechanical broom, and hand brooming if necessary, to remove all vegetation, loose material, and dust.

Trial areas: Trial areas are to be laid to determine the precise rate of spread required for the binder and chippings. The rate of spread for the binder is to be from 10 to 12 sq yd/gallon, starting at 12 sq yd/gallon and working towards 10 if the former rate does not cover the entire surface. The coated chippings are to be applied at a rate of approximately 250 sq yd/ton, the rate to be that which ensures complete coverage of the binder after final sweeping.

Application of surface binder: The surface binder during application is to be maintained at a temperature between 300° and 320° F (149° and 160° C). At junctions with surfaces not to be dressed, clean lines are to be defined by masking with waterproof building paper, or other impervious strips, at the start or end, as appropriate, of distributor runs. The binder is to be applied at the selected rate without variation, in such a manner that a film of uniform thickness results. Particular care is to be taken to avoid dripping, spilling, and areas of excessive thickness.

Application of coated chippings: The temperature of the heated and coated chippings when applied to the sprayed surface binder is to be not less than 180° F (83° C). Before and during the rolling operation, any bald patches are to be made good with fresh chipping.

Rolling: The coated chippings are to be rolled immediately after spreading, before loss of heat. At least one complete coverage will be made by each of the three rollers, following closely one behind the other.

Final sweeping and rolling: Within 3 days of the gritting operation, all loose chippings are to be swept from the surface with hand brooms, loaded into lorries, and removed from the airfield. The surface is then to be further rolled with at least three complete coverages of the area. The finished surface is to have all chippings firmly adherent; is to be of uniform surface texture and colour, entirely free from surface irregularities due to scabbing, scraping, dragging, droppings, excessive overlappings, or faulty lane or transverse junction, or other defects; and is to be left clean and tidy to the satisfaction of the S.O. Under no circumstances are swept up chippings to be reused.

APPENDIX C

FARNBOROUGH RAFB, ENGLAND – RUNWAYS 26 and 36

Runways tested:

07/25 Main runway: Grooved asphalt, constructed 1961 (runway 26)
Main construction, asphalt (constructed 1956)

00/18 Friction course: Constructed 1965-1966 (Runway 36)
Main construction, rolled asphalt (constructed 1965-1966)

12/30: Rolled asphalt

Sawcut Grooving of Asphalt Surface

The surface of the asphalt wearing course is to be grooved across the runway at right angles to the runway edges with grooves which follow across the runway in a continuous line without break. The sawing machine is to incorporate a minimum of 12 circular segmented diamond saw blades set to form grooves in the surface 1/8 in. wide by 1/8 in. deep at approximately 1 in. centres. Sawing apparatus is to include water tankers and pressure sprays.

Open-graded Macadam Friction Course (Runway 00/18)

Aggregate: Crushed rock from one of the following: basalt, gabbro, granite, hornfels or porphyry.
Crushing value: Less than 16%
Flakiness index: Less than 25%
Stripping: As in clause 201.

Binder: Petroleum bitumen, Grade 200 pen.

Filler: As clause 114, except that at least 1½% by weight of total mixed material is to be hydrated lime.

Aggregate grading (including filler):

BS sieve	Percent by weight passing
1 in.	100
3/4 in.	90 to 100
1/2 in.	60 to 75
1/4 in.	25 to 35
1/8 in.	12 to 18
No. 200	3 to 5

APPENDIX C

FARNBOROUGH RAFB, ENGLAND – RUNWAYS 26 and 36 – Continued

Binder content: Percentage by weight of total mixed material, 4.25 to 2.75

Mixing temperature: Aggregate, 175° F to 250° F
Binder, 200° F to 275° F

Rolling temperature: Not less than 160° F.

Roller weight: As clause 125, except that rollers are to weigh not less than 6 tons or more than 10 tons.

Compacted thickness: $1\frac{1}{4}$ in.

Tack coat: Bitumen emulsion over the asphalt wearing course at 15 to 20 sq yd/gal.

Surface accuracy: As clause 205(b)

NOTE: This mixture is for runways only (excluding runway ends). It allows the free penetration of surface water to the underlying layer which must be a densely graded impervious wearing course of high stability similar to Schedule I, V(1), or V(2). It should be of uniform compacted thickness throughout and is not suitable over deformed or poorly shaped surfaces. Materials and workmanship generally are to be in accordance with Section I and Part A of Section II of the Specification.

SCHEDULE I (for aircraft with tyre pressures exceeding 150 lb/sq in.)

Rolled Asphalt (Marshall Method): Wearing Course (Runway 12/30)

MATERIALS

Aggregate: Coarse – Rock or crushed gravel
Fine – Rock or sand

Filler: Limestone or Portland cement

Binder: Petroleum bitumen, Grade 70 pen.

Combined dry aggregate: Particle-size distribution of combined coarse and fine aggregate and added filler as follows:

APPENDIX C

FARNBOROUGH RAFB, ENGLAND – RUNWAYS 26 AND 36 – Continued

1/2 in. nominal size aggregate		3/4 in. nominal size aggregate	
BS sieve	Percentage by weight passing	BS sieve	Percentage by weight passing
		1 in.	100
3/4 in.	100	3/4 in.	89 to 100
1/2 in.	86 to 100	1/2 in.	78 to 90
3/8 in.	78 to 90	3/8 in.	69 to 83
1/4 in.	66 to 79	1/4 in.	60 to 75
1/8 in.	52 to 65	1/8 in.	49 to 63
No. 14	34 to 49	No. 14	35 to 49
No. 36	19 to 33	No. 36	22 to 33
No. 100	9 to 17	No. 100	13 to 20
No. 200	3 to 6	No. 200	2 to 6

LABORATORY DESIGN MIXTURE

Combined dry aggregate: The aggregate is to be of the nominal size appropriate to the thickness of the compacted course and in accordance with the preceding table. Particle-size distribution to give a smooth curve throughout the range of sizes.

Optimum binder content: Between 5% and 7.5%; the exact percentage to be as for scored concrete (see data for Yeovilton RNB)

Stability: Not less than 1800 lb.

Flow: Not more than 0.16 in.

Voids in the total mixture: Between 3% and 4%

Voids filled with binder: Between 76% and 82%

JOB STANDARD MIXTURE

Combined dry aggregate: As used for the laboratory design mixture, modified, if necessary, in accordance with clause 1025.

Binder content: As determined by the laboratory design mixture, modified, if necessary, in accordance with clause 1025.

Stability: The value determined by test on specimens of the modified mixture (to be not less than 1800 lb).

Flow: Not more than 0.16 in.

Voids in the total mixture: The value determined by test on specimens of the modified mixture (to be between 3% and 4%).

Voids filled with binder: The value determined by test on specimens of the modified mixture (to be between 76% and 82%).

PLANT MIXTURES: All values are to be as approved for the job standard mixture, except that the following variations will be permitted:

Combined dry aggregate: Aggregate retained on 1/8 in. or larger BS sieve: ±4%.

Aggregate passing 1/8 in., No. 14, No. 36, or No. 100 BS sieve: ±3%.

Aggregate passing No. 200 BS sieve: ±1.5%

Binder content: ±0.3%

Voids in the total mixture: ±1%

Voids filled with binder: ±5%

Stability: Not less than 1500 lb.

Flow: Not more than 0.16 in.

Temperature: Binder and aggregate between 300° F (149° C) and 350° F (177° C), and within 25° F (14° C) of each other at the time of mixing.

REQUIREMENTS FOR LAYING PLANT MIXTURES

Compacted thickness of course: As indicated and within the following limits:
For 1/2 in. nominal size aggregate: $1\frac{1}{4}$ in. to 2 in.
For 3/4 in. nominal size aggregate: $1\frac{1}{2}$ in. to $2\frac{1}{2}$ in.

Laying temperature: Between 275° F (135° C) and 325° F (163° C)

Rolling temperature: As necessary to achieve the field density specified but not less than 250° F (122° C)

SCHEDULE II (for aircraft with tyre pressures exceeding 150 lb/sq in.)

Rolled Asphalt (Marshall Method): Base Course (Runway 12/30)

MATERIALS

Aggregate: Coarse – Rock or crushed gravel
Fine – Rock or sand

APPENDIX C

FARNBOROUGH RAFB, ENGLAND – RUNWAYS 26 AND 36 – Continued

Filler: Limestone or portland cement

Binder: Petroleum bitumen, Grade 70 pen.

Combined dry aggregate: The particle-size distribution of the combined coarse and fine aggregate and added filler is to be in accordance with the following table:

3/4 in. nominal size aggregate		1 in. nominal size aggregate	
BS sieve	Percentage by weight passing	BS sieve	Percentage by weight passing
1 in.	100	$1\frac{1}{2}$ in.	100
3/4 in.	76 to 100	1 in.	78 to 100
1/2 in.	64 to 89	1/2 in.	56 to 80
1/4 in.	46 to 71	1/4 in.	40 to 64
1/8 in.	32 to 58	1/8 in.	30 to 52
No. 14	20 to 42	No. 14	18 to 38
No. 36	12 to 28	No. 36	11 to 25
No. 100	6 to 16	No. 100	5 to 15
No. 200	4 to 8	No. 200	3 to 7

LABORATORY DESIGN MIXTURE:

Combined dry aggregate: Nominal size appropriate to the thickness of the compacted course and in accordance with the preceding table. Particle-size distribution to give a smooth curve throughout the entire range of sizes.

Optimum binder content: Between 4% and 8%.

Stability: Not less than 1800 lb

Flow: Not more than 0.16 in.

Voids in the total mixture: Between 3% and 5%

Voids filled with binder: Between 67% and 77%

JOB STANDARD MIXTURE:

Combined dry aggregate: As used for the laboratory design mixture, modified, if necessary, in accordance with clause 1025.

APPENDIX C

FARNBOROUGH RAFB, ENGLAND – RUNWAYS 26 AND 36 – Concluded

Binder content: As determined by the laboratory design mixture, modified, if necessary, in accordance with clause 1025.

Stability: As determined by test on specimens of the modified mixture (not less than 1800 lb)

Flow: Not more than 0.16 in.

Voids in the total mixture: As determined by test on specimens of the modified mixture (between 3% and 5%).

Voids filled with binder: As determined by test on specimens of the modified mixture (between 67% and 77%).

PLANT MIXTURES: All values as approved for the Job Standard Mixture, except for the following variations:

Combined dry aggregate: Aggregate retained on 1/8 in. or larger BS sieve: ±5%
Aggregate passing 1/8 in., No. 14, No. 36 or No. 100 BS sieve: ±4%
Aggregate passing No. 200 BS sieve: ±1.5%

Binder content: ±1%

Voids filled with binder: ±5%

Stability: Not less than 1500 lb

Flow: Not more than 0.16 in.

Temperature: Binder and aggregate between 300° F (149° C) and 350° F (177° C) and within 25° F (14° C) of each other at the time of mixing.

REQUIREMENTS FOR LAYING PLANT MIXTURES:

Compacted thickness of course: As indicated, within the following limits:
For 3/4 in. nominal size aggregate: $1\frac{1}{2}$ in. to $2\frac{1}{2}$ in.
For 1 in. nominal size aggregate: 2 in. to $3\frac{1}{2}$ in.

Laying temperature: Between 275° F (135° C) and 325° F (163° C)

Rolling temperature: As necessary to achieve the density specified, but not less than 250° F (122° C).

APPENDIX C

SEMBACH AIR BASE, GERMANY – RUNWAY 27

Test runway: 07/25 Length, 7877 ft Width, 150 ft (Overruns, east, 300 ft; west, 300 ft)	Landing approach 25
Construction history	Constructed in 1952, consists of 12 in. of concrete, type B 450 (1:3.5). In 1964 partial repairs, consisting of antiskid and joint sealing, for a contract cost of $15 735; antiskid material approximately 1/8 in. Aggregate size is 1 to 30 mm and consists of angular metamorphic material. Antiskid material consists of aggregate laid on approximately 1/8 in. of macadam. Scuffing of the antiskid area is prevalent by larger aircraft, such as the C-141A or C-130 airplanes
Longitudinal elevations (in feet)	07 end

0 + 00	-1013
3 + 00	-1014
6 + 50	-1015
13 + 00	-1020
18 + 00	-1026
26 + 00	-1031
32 + 00	-1034
42 + 65	-1033
50 + 85	-1030
65 + 61	-1041
75 + 45	-1051
78 + 77	-1049

Precipitation	Annual mean rainfall – 25.7 in. Annual mean snowfall – 17.9 in. Highest month – January, 6.9 in. of snow Lowest month – November, 1.29 in. of rain
Drainage	Slight runoff toward south side of runway No ponding was observed

APPENDIX C

TEMPELHOF CENTRAL AIRPORT, GERMANY – RUNWAY 29

Test runway: 09R/27L
Length, 5267 ft
Width, 140 ft

Landing approach 09R

Construction in 1948

Subgrade: SC-SP (CBR 15 in. average).

Base: 18 in. rubble (brick, rubble, sandstone).

Pavement: $4\frac{1}{2}$ in. asphalt penetration macadam.

Construction in 1964

Overlay: $1\frac{1}{2}$ in. hot mix asphalt concrete.

Aggregate size:
22.5% size 8 to 12 mm (3/8 to 1/2 in.)
17.5% size 5 to 8 mm (No. 4 to 3/8 in.)
17.5% size 2 to 5 mm (No. 10 to No. 5)

Aggregate gradation:
22.5% chips 8 to 12 mm (note that 314 000 sq ft of original antiskid coat at center grooved in 1968)
17.5% chips 5 to 8 mm
17.5% chips 2 to 5 mm
17.5% crushed sand 0.09/2 mm (No. 200)
15.0% pit sand 0.09/2 mm (No. 200)
10.0% filler, mineral
100.0%
+6% bitumen B 80
Chips are double crusher run, processed, basaltic rock

Construction in 1966

Antiskid slurry coat consisting of a tack coat of bitumen-latex compound, applied hot with strewn-in and rolled noncoated aggregate 3 to 5 mm (No. 7 to No. 5), over full length and width of runway.

Construction in 1968

Grooved, 3/8 in. wide by 3/8 in. deep by $1\frac{1}{2}$ in. pitch; transversely, 60 ft wide from center of runway between thresholds 9R and 27L plus 250 ft of overruns. Cost $0.09 per sq ft (against $0.08 cost for antiskid surface). Considerable amounts of rubber accumulate and must be removed twice a year.

APPENDIX C

TEMPELHOF CENTRAL AIRPORT, GERMANY – RUNWAY 29 – Concluded

Transverse slope	1.5%
Longitudinal grade	Between thresholds: 0.228% Maximum at station 22 + 00 and 30 + 00 = 0.75%
Precipitation	Annual rainfall – 21.99 in. Annual snowfall – 15.7 in.
Drainage	No ponding noticed on antiskid surface and grooved runway.

APPENDIX C

McCHORD AFB, WASHINGTON – RUNWAY 30

Test runway: 16/34 Length, 11 600 ft Width, 150 ft	Landing approach 16
Construction in 1939	Original 5700 ft runway consisted of 3 in. AC. Surface finish and aggregate characteristics not known.
Construction in 1951	Runway extended on 16 end consisted of $3\frac{1}{2}$ in. of AC for 5100 ft and 13 in. of PCC for 800 ft. Surface finish and aggregate characteristics not known.
Construction in 1953	4700 ft of 34 end overlayed with $1\frac{1}{2}$ in. in AC. Surface finish and aggregate characteristics not known.
Construction in 1965	Slurry seal applied to 1200 ft on 16 end and 2000 ft on 34 end.
Longitudinal grade	Not available
Transverse slope	Not available
Precipitation	Annual precipitation – 38 in. Annual snowfall – 13.9 in. Highest month – November (5.9 in.) Lowest month – July (0.8 in.) Frost penetration negligible
Drainage	Effective, good
Rubber deposit removal	One unsuccessful attempt to remove rubber spots from the runway with a carbon engine cleaner was made. No costs or time for removal is available.
Pavement condition	Excellent

APPENDIX C

LITTLE ROCK AFB, ARKANSAS – RUNWAY 31

Test runway: 24/06 Length, 12 000 ft Width, 200 ft	Landing approach 24
Construction in 1955	5 in. to 7 in. asphalt concrete over 6 in. crushed rock base and 14 in. subbase.
Construction in 1965	$1\frac{1}{2}$ in. overlay surface course of asphalt concrete (AP-3, 85-100). Large aggregate, 3/4 in. maximum size, crushed limestone from Granite Mountain at Little Rock, Arkansas.
Transverse slope	Crown, $1\frac{1}{2}\%$
Longitudinal grade (West to East)	Station 00 + 00 - 30 + 00 +0.77% 30 + 00 - 49 + 00 0.00% 49 + 00 - 62 + 00 +0.20% 62 + 00 - 103 + 00 -0.45% 103 + 00 - 120 + 00 -0.25%
Precipitation	Rain – 48.6 in. Snow – 5.0 in. Highest month – March (3.7 in.) Lowest month – October (1.3 in.)
Drainage	Excellent.
Pavement condition	Excellent. Some subgrade consolidation in alert taxi path for B58 airplanes.

APPENDIX C

SCOTT AFB, ILLINOIS – RUNWAY 32

Test runway: 13/31 Length, 7038.5 ft Width, 150 ft	Landing approach 31	
No construction details		
Transverse slope	1% off center line	
Longitudinal grade	0 + 00 to 11 + 00	-0.62%
	11 + 00 to 12 + 00	-0.46%
	12 + 00 to 16 + 60	-0.62%
	16 + 60 to 38 + 11	-0.21%
	38 + 11 to 48 + 11	-0.22%
	48 + 11 to 59 + 36	+0.02%
	59 + 36 to 60 + 36	-0.15%
	60 + 36 to 70 + 36	Level
Precipitation	Rain – 39.2 in. Snow – 15.0 in.	
Drainage	Good, except for slower drainage at intersection	
Pavement condition	Good	

APPENDIX C

NELLIS AFB, NEVADA – RUNWAY 34

Test runway: 03L/21R Length, 10 059 ft Width, 150 ft	Landing approach 03L
Construction in 1965	3 in. full depth AC; 14 in. base, CBR = 100; 6 in. base, CBR = 80.
	Surface – Coarse, rough asphalt concrete.
	Characteristics of large aggregate, 3/4 in. maximum, open-graded, crushed desert rock from the Gibson Pit at Las Vegas, 3 to 5% passing No. 200 sieve.
Construction in 1969	Fog seal applied in March 1969. Some rubber buildup on ends of runway (not removed).
Transverse slope	Slopes from west to east on a $1\frac{1}{2}\%$ incline (full width).
Longitudinal grade	Average of 0.036% north end is highest and runway has three slight overt curves.
Precipitation	Annual precipitation – 3.32 in. Annual snowfall – Trace. Highest month – April (0.5 in.). Lowest month – June (trace).
Drainage	Quite effective, no problem.
Pavement condition	Good to very good, some longitudinal cracks at load lines. Fog seal is off in much of traffic area but still on in untraveled areas.
Future improvement	Slurry seal to be added in October 1969 (projected cost, $22,000).

APPENDIX C

MARHAM RAFB, ENGLAND – RUNWAY 38

Test runway: 06/24 (Main runway)

Open graded macadam

Friction course (3/4 in.)

Date of surfacing – April to November 1966

Main construction – rolled asphalt

Aggregate: Crushed rock from one of the following groups:
Basalt, gabbro, granite, hornfels, or porphyry

Crushing value: Not more than 16%

Flakiness index: Not more than 25%

Stripping: As clause 1004

Binder: Petroleum bitumen, grade 200 pen.

Filler: As clause 1008 except that at least $1\frac{1}{2}$% by weight of total mixed material is to be hydrated lime.

Aggregate grading (including filler):

BS sieve	Percent by weight passing
1/2 in.	100
3/8 in.	90 to 100
1/4 in.	40 to 55
1/8 in.	22 to 28
No. 200	3 to 5

Binder content: Percentage by weight of total mixed material, 4.75 to 5.25

Mixing temperature:

Aggregate: 175° F to 250° F

Binder: 200° F to 275° F

Rolling temperature: Not less than 160° F

Roller weight: As clause 1019, except that rollers are to weigh not less than 6 tons or more than 10 tons.

Compact thickness: 3/4 in.

Tack coat: Bitumen emulsion over the asphalt wearing course at 15/20 sq yd/gal.

Surface accuracy: As clause 1021(b).

APPENDIX C

MARHAM RAFB, ENGLAND – RUNWAY 38 – Concluded

This mixture is for runways only, excluding runway-ends. It allows the free penetration of surface water to the underlying layer, which is to be a densely graded impervious wearing course of high stability in accordance with schedule I or V. It is to be of uniform compacted thickness throughout and materials and workmanship generally are to be in accordance with subsection A of this part of this specification.

APPENDIX C

LANDING RESEARCH RUNWAY 4/22 AT NASA WALLOPS STATION, VIRGINIA

Data were collected from the landing research runway at NASA Wallops Station, Virginia (fig. C1) and from 34 other military and civil runways in the United States and Europe. The research runway is 150 feet wide and 8750 feet long. The test area is 50 by 3800 feet and consists of five grooved and four ungrooved sections, each 350 feet long, and 1 ungrooved section 650 feet long. Section J, which is not shown in figure C1, was added northeast of section A; this section is a grooved section 350 feet long. The grooves on all grooved sections except section J are 1/4 inch wide, 1/4 inch deep, and spaced 1 inch apart. Section J has the groove configuration used at Seymour Johnson Air Force Base, N.C.: grooves 1/4 inch wide and deep, spaced 2 inches apart, and arranged in alternate 2-foot strips of grooved and ungrooved sections of runway. The test section was constructed in the center of the runway to provide a safety overrun at each end. A groove 1/4 inch wide by 1 inch deep surrounds each test section to support the rubber dams used to control the water depth. The surfaces for sections A to J are identified as follows:

Section A: Canvas-belt drag finished concrete, ungrooved
Section B: Canvas-belt drag finished concrete, grooved
Section C: Burlap drag finished concrete, grooved
Section D: Burlap drag finished concrete, ungrooved
Section E: Gripstop transition surface
Section F: Small-aggregate asphalt, ungrooved
Section G: Small-aggregate asphalt, grooved
Section H: Large-aggregate asphalt, grooved
Section I: Large-aggregate asphalt, ungrooved
Section J: Burlap drag finished concrete, grooved

APPENDIX C

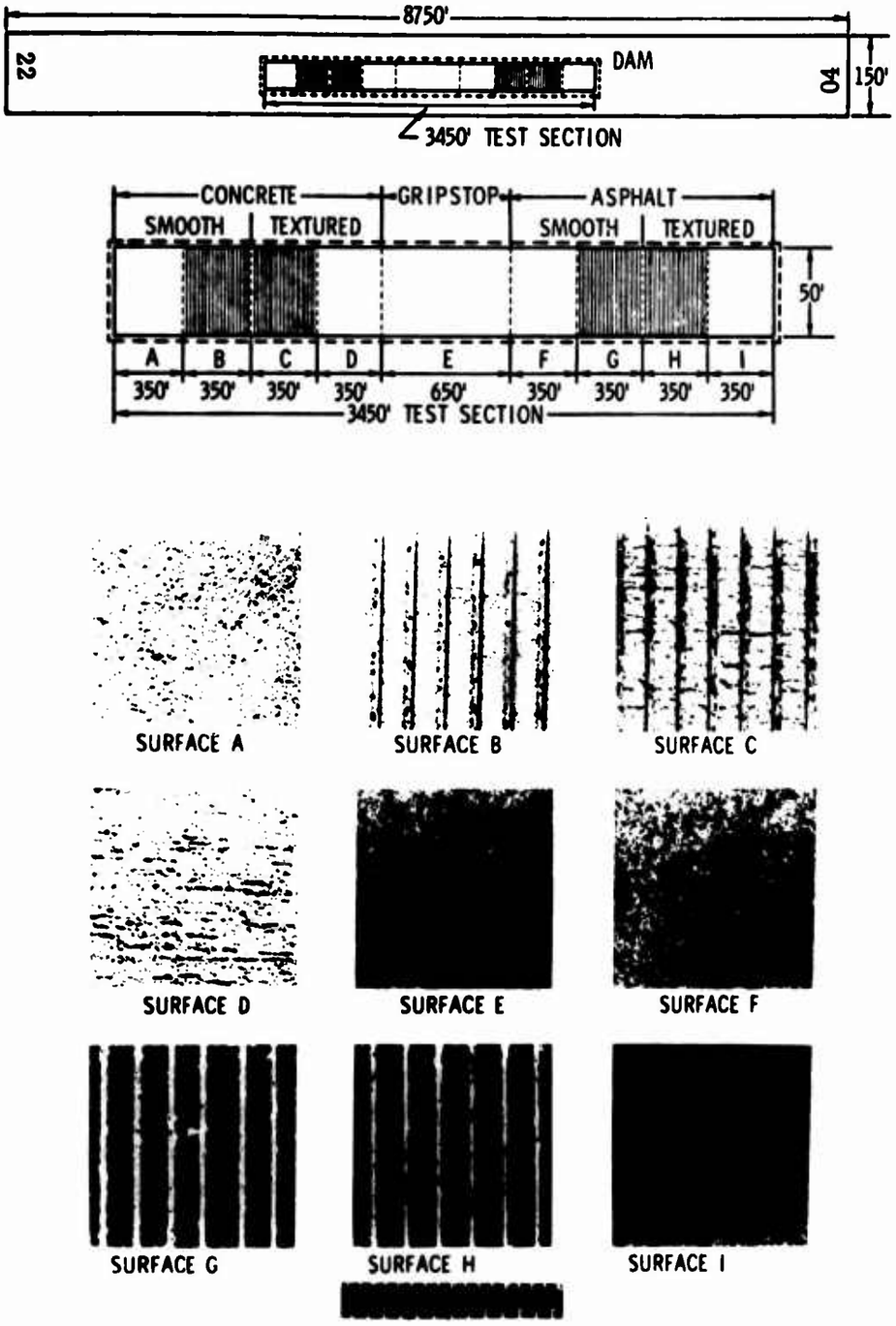


Figure C1.- Landing research runway at Wallops Station, Virginia.

APPENDIX D

A REPORT ON THE RESULTS FROM THE MINISTRY OF TECHNOLOGY RUNWAY FRICTION METER (MU-METER) DURING JOINT TRIALS IN THE UNITED KINGDOM WITH THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION 15 TO 25 JULY 1969

By R. W. Sugg
Ministry of Aircraft Supply

Summary

Speed-friction results are given from the Ministry of Technology runway friction meter (Mu-meter) which was used in a joint trial with the National Aeronautics and Space Administration in the United Kingdom on seven different surfaces. An investigation was made into the ability of the friction meter to correlate with aircraft stopping distances, to classify runways, and to indicate on a continuous record the position and extent of areas where surface contamination has reduced its friction values.

Introduction

Over the last 12 years the Ministry of Technology (now Ministry of Aircraft Supply) has been engaged on a research programme aimed at defining the factors which cause low friction on wet runways with a view to eradicating the problem and, where this was difficult, to introduce equipment to give a warning that such conditions existed. One of the conclusions of this work was the verification that the greatest single factor which could improve friction between an aircraft tyre and runway was the texture and water-holding capacity of the surface itself. Unfortunately, runways are expensive to construct or resurface and once laid must be expected to last for a considerable time; also, the best friction surfaces are often the most expensive to apply. These facts coupled with the fact that aircraft stopping distances are increasing, even in the dry, directed the Department's attention to use of vehicular equipment which might adequately predict these stopping distances, and to warn of the presence and effect of aquaplaning conditions, snow, slush, and ice.

In 1964 a series of trials were conducted on four different types of runway texture wher wet by using two types of decelerometers fitted to the same road vehicle and the results, up to a speed of 50 mph, were compared with those from a heavy load friction vehicle fitted with an aircraft wheel, brake, tyre and braking system, using tyre pressures between 100 and 160 psi and a vertical load of 3.5 tons. It was found that little correlation

existed. Later, a comparison was made between decelerometers and an aircraft when it was found that the former when used at 30 mph did not even place the runway surfaces in the same friction order as the aircraft. This result was the final proof that this method of predicting aircraft stopping distances on wet runways could be misleading.

The next series of trials occurred some years later when the opportunity arose to compare the performance of a Hunter aircraft weighing approximately 17 000 lb and the heavy load friction vehicle used above and which, in this instance, was fitted with a Hunter wheel, brake, tyre and braking system. The same tyre pressures, wheel loads, wetness conditions, and surfaces were used. It was thought that under such closely comparable test conditions, there should not only be correlation, but the actual figures themselves should be the same. This however was not the case and it led to the inevitable conclusion that correlation between the friction values of aircraft and ground vehicles was most unlikely and another method must be tried.

In 1966, research by the Ministry of Technology indicated there was a possibility of predicting stopping distances if a device could be produced which would place friction surfaces in the same order as those of an aircraft; consequently, that year the Ministry of Defence raised an air staff requirement for an equipment which would meet the following points:

(1) Accurately measure runway friction

(2) Present a continuous record of friction against distance

(3) Be capable of giving a fair prediction of aircraft stopping distances

(4) Be operated by a single person

(5) Be towed behind a service vehicle

(6) Be easy to maintain

(7) Forecast aquaplaning conditions

(8) Operate at -26° C

With this requirement in mind, the Ministry of Technology developed the friction meter shown in figure D1, generally called the Mu-meter. It consists of three wheels, two of which are mounted at the ends of independently moveable arms, pivoted at the towing point and adjusted to a specific toe-out angle. When towed, the resulting side loads imposed on the arms are sensed by a pressure capsule mounted between them and the pressure variations transmitted to a pen recorder, the side load being a measure of the surface friction. The third wheel drives the recorder chart. The recording apparatus includes an integrator which enables the average friction value to be calculated over any distance. An event pen operated by the driver can be used to mark the record at any selected point.

APPENDIX D

The total weight of the equipment is about 530 lb of which about 250 lb is removeable ballast. The tyres are 16 inches in diameter and 4 inches wide operating at a pressure of 10 psi and are closely controlled in manufacture to maintain consistency of results. The length, width, and height are 60, 32, and 34 inches, respectively, and the chart is arranged to move at 450 feet per inch and each chart roll has a total capacity of approximately 40 miles.

So that the equipment can be operated by a single person who may have to remain on listening watch in the towing vehicle whilst on an active runway, a remote recorder (fig. D2) has been developed which is actuated by the friction recording mechanism in the friction meter itself. In fact, a set of three remote recorders can be provided so that each may be switched on to record and hold the average friction values for each third of a runway; no time is then spent on the actual runway in writing down numbers.

To enable a towing speed to be used which is both within the capability of a normal road vehicle and which will still discern the presence of aquaplaning, a tyre pressure of 10 psi was chosen. When towed at 40 mph, this pressure gives a speed equivalent to 1.2 times the theoretical aquaplaning speed. To make sure that tread wear would have no effect on the results, a plain pattern tyre is used.

Because the depth of water on a runway can affect surface friction and with the object in mind that the friction meter would be used in the future to classify runways in their friction order, the opportunity was taken to test a self-contained watering device which had recently been developed to deposit a depth of approximately 0.15 inch ahead of each test tyre. The opportunity was also taken to record James brake decelerometer readings with an instrument provided by NASA and fitted to a Land Rover.

Test Method

A 2000-foot length of runway was marked out and prior to aircraft trials, the friction meter towed by a high-speed vehicle measured the friction at several speeds in the dry (usually at 40, 60, and 80 mph). When the C-141A aircraft was airborne, four and later three 2500-gallon water bowsers with 15-foot spreader bars watered the test area depositing a calculated depth of nearly 0.1 inch of water. This watering took approximately 8 minutes and the bowsers immediately cleared the runway; the C-141A then carried out its braked run. As soon as the aircraft cleared the runway, the test vehicles took over, the friction meter making runs at 40, 60, and 80 mph in quick succession and the Land Rover with the James brake decelerometer locking its wheels for 1 second at 30 mph. Sometimes before the wet aircraft run and sometimes after the runway had dried out, the friction meter made runs at 40, 60, and 80 mph using its self-wetting device.

APPENDIX D

Test Airfields

The runways, location, surface, and test dates were as follows:

17 July, Farnborough main runway, saw-cut-grooved asphalt 1 in. by 1/8 in. by 1/8 in.

18 July, Farnborough North-South runway, porous friction course

19 July, RNAS Yeovilton, wire-brushed and scored concrete

21 July, RAF Station Marham main runway, porous friction course

21 July, RAF Station Marham subsidiary runway, old concrete

25 July, RAF Station Waddington main runway, 1/8 in. surface dressing on rolled asphalt

In addition, the friction meter only tested the asphalt runways at Farnborough and RAF Station Wittering.

Results and Discussion

All the average friction meter results are given in table DI and, as was to be expected, the porous friction courses at Farnborough and RAF Marham gave the highest values comparable to the 1 in. by 1/4 in. by 1/4 in. grooved surfaces at NASA Wallops Station, Virginia, U.S.A. The friction meter results on the scored and wire-brushed surfaces at RNAS Yeovilton were lower than those for the Farnborough 1 in. by 1/8 in. by 1/8 in. grooved asphalt, the 1/8 in. chipping at RAF Waddington and asphalt at RAF Wittering, the last was not tested by the C-141A. The friction meter indicated that areas of the Wittering runway which had long black streaks gave values at 60 mph of 0.55 as against the usual 0.73. These marks may have been caused by the hot downblast of VTOL aircraft melting the asphalt and destroying its micro texture. (See fig. D3.) In certain areas of Waddington, the friction meter trace showed a reduction in value from 0.75 to 0.55 and this reduction was possibly due to the hot air blowers used in snow clearance operations damaging the surface; it was also noticed that in certain areas, repairs to runways had not always achieved the same friction values as for the surrounding areas. It was also shown that the white centre line paint could give a friction value as low as 0.30 and runway materials used in run-up or holding areas could be as low as 0.40. The ability of the friction meter to identify the extent and effect of rubber in spin up areas (not on the runways listed previously) is shown in figure D4. Values from the James brake decelerometer are given in table DII which demonstrate again that decelerometers in road vehicles are of little use in measuring friction under wet conditions.

Conclusions

The continuous trace from the friction meter gave a clear indication of low friction areas caused by the use of special surfaces at runway ends, paint markings, rubber

deposits, damage due to snow and ice removal equipment, repairs to the surface, and jet blast caused by VTOL aircraft. Decelerometers in vehicles are of little use to measure wet runway friction for aircraft purposes. From preliminary aircraft data, it would appear that the friction meter has once again placed the runway surfaces in the same friction order as the aircraft. By using the self-wetting system, it was possible to provide a pictorial representation of the friction over the whole runway length except for approximately 300 feet at the start and 50 feet at the end which are required for acceleration and stopping.

Acknowledgements

The fact that it was possible to complete successfully a trial of this type in 10 days was primarily due to the unusually good weather and to the cooperation received from the aerodrome operators (MOD (Air), MOD (Navy), and the RAE), the USAF-NASA team, the control of the project by the Cranfield Institute of Technology (I. Beaty).

APPENDIX D

TABLE DI. - MU-METER RESULTS ON TEST AREAS

Date	Surface	Wetting	Speed	Friction	Remarks
			Farnborough		
July 14, 1969	Grooved asphalt	D y	20	0.82	
July 14, 1969			60	.85	
July 14, 1969			80	.815	
July 14, 1969		Bowser	40	.72	
July 14, 1969			80	.60	
July 16, 1969	Porous surface	Dry	20	.84	
July 16, 1969			80	.825	
July 16, 1969		Bowser	40	.78	
July 16, 1969			80	.72	
			RNAS Yeovilton		
July 19, 1969	Wire combed concrete	Dry	20	0.76	Texture depth 1.370 mm (0.054 in.)
			40	.79	
			80	.79	
		Bowser	40	.65	Mu-meter runs delayed due to
			60	.71	aircraft - runway drying out
			80	.68	
		Self	40	.63	
			80	.57	
	Scored concrete	Dry	20	.76	Texture depth 0.830 mm (0.033 in.)
			40	.80	
			80	.78	
		Bowser	40	.63	
			60	.61	
			80	.54	
		Self	40	.63	
			80	.59	
			RAF Marham		
July 22, 1969	Porous surface	Dry	40	0.87	
			60	.88	
			80	.84	
		Bowser	40	.83	
			60	.82	
			80	.74	
		Self	40	.83	Repaired area gave 0.70
			60	.80	
			80	.78	Repaired area gave 0.50
	Old concrete	Dry	40	.79	Texture depth 0.435 mm (0.017 in.)
			80	.70	
		Bowser	40	.52	
			60	.45	
			80	.44	
		Self	40	.55	
			60	.485	
			80	.415	
	Zorcon areas	Self	40	.4	
	Center line point	Self	30	.3	
			RAF Wittering		
July 24, 1969	Asphalt	Dry	40	0.84	
		Self	40	.74	There were low friction areas in
			60	.73	streaks which gave 0.55 at 60 mph
			80	.65	
			RAF Waddington		
July 25, 1969	1/8 in. surface dressing	Dry	40	0.845	
			60	.859	
		Self	40	.76	
			60	.756	
			80	.70	
		Bowser	40	.62	
			60	.50	
			80	.45	
			Farnborough		
July 30, 1969	Grooved asphalt	Self	40	0.84	
			60	.85	
			80	.82	
	Porous surface	Self	40	.85	
			60	.82	
			80	.80	

APPENDIX D

TABLE DII.- JAMES BRAKE DECELEROMETER RESULTS ON TEST AREAS AT 30 MPH

[The James brake decelerometer was damaged after the trials at Marham; consequently, no readings are available for Waddington]

Surface	Vehicle deceleration			
	Surface dry		Surface wet	
		Average		Average
Farnborough grooved asphalt	0.60 .73 .76 .76	0.71	0.77 .77 .60 .60 .67	0.68
Farnborough porous asphalt	0.73 .72 .75	0.73	0.79 .75 .80	0.78
Yeovilton scored concrete	1.0 .85 .85	0.90	0.76 .78 .75	0.76
Yeovilton wire brushed concrete	0.84 .83 .79	0.82	0.88 .98 .98 .80	0.91
Marham old concrete	0.90 .84 .88	0.88	0.89 .82 .82	0.84
Marham porous asphalt	0.90 .90 .87	0.89	0.88 .85 .92	0.88

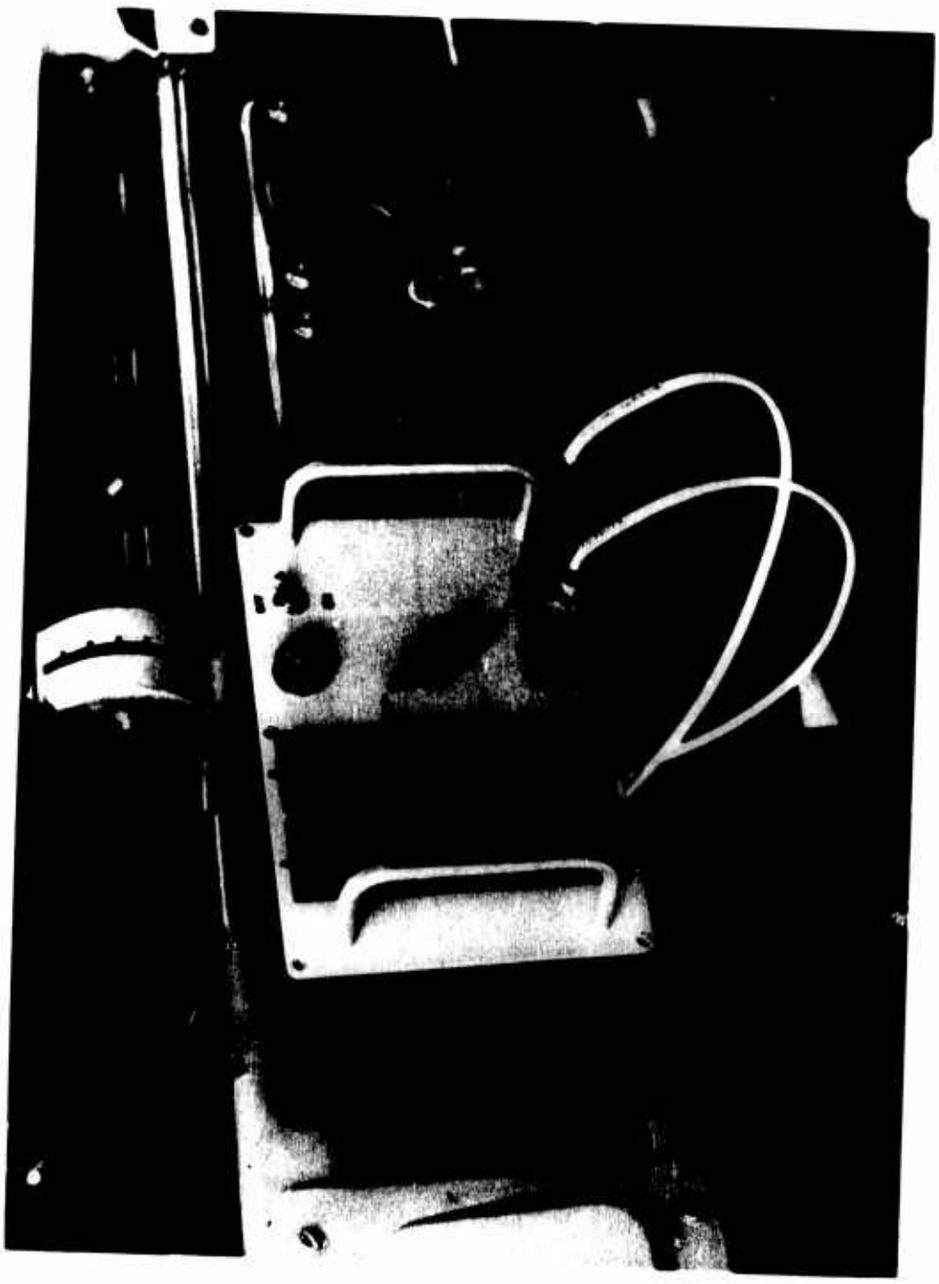
APPENDIX D



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Figure D1.- Runway friction meter (Mu-meter).

APPENDIX D



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Figure D2.- Remote recorder.

APPENDIX D

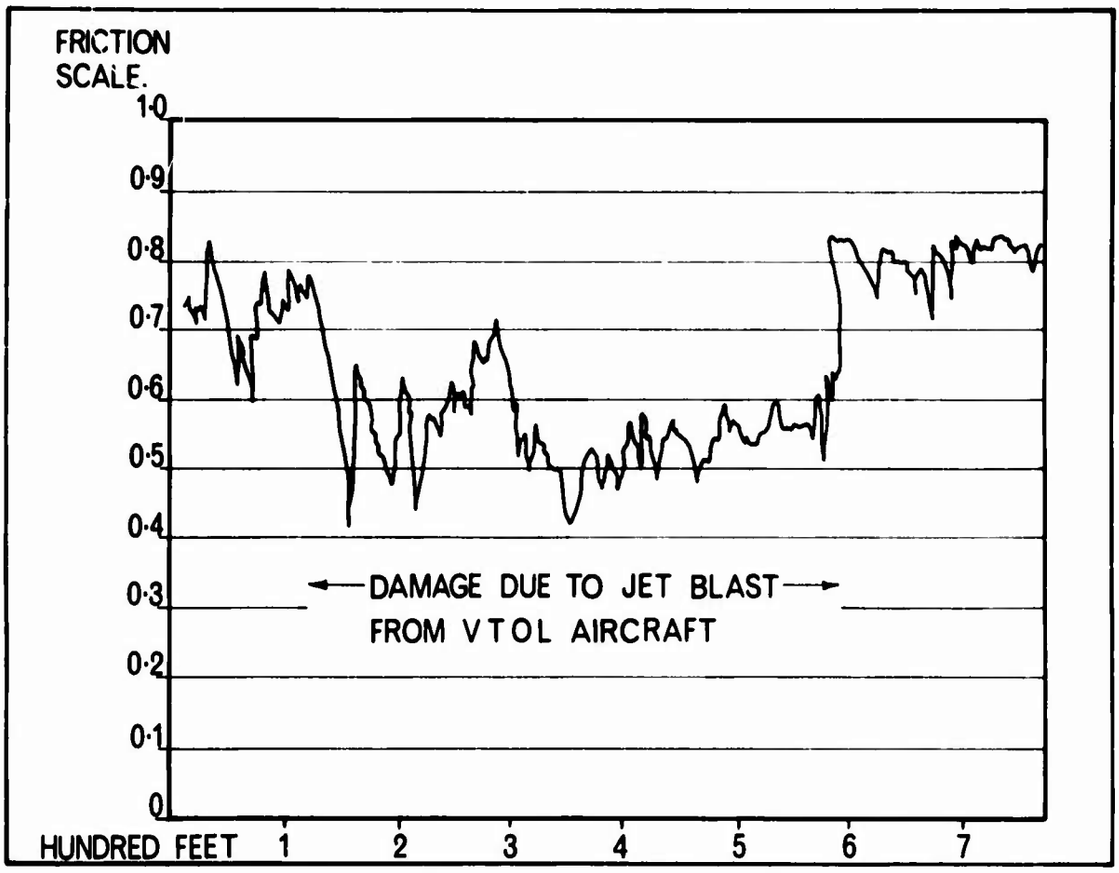


Figure D3.- Friction meter record of runway damage due to jet blast from VTOL aircraft.

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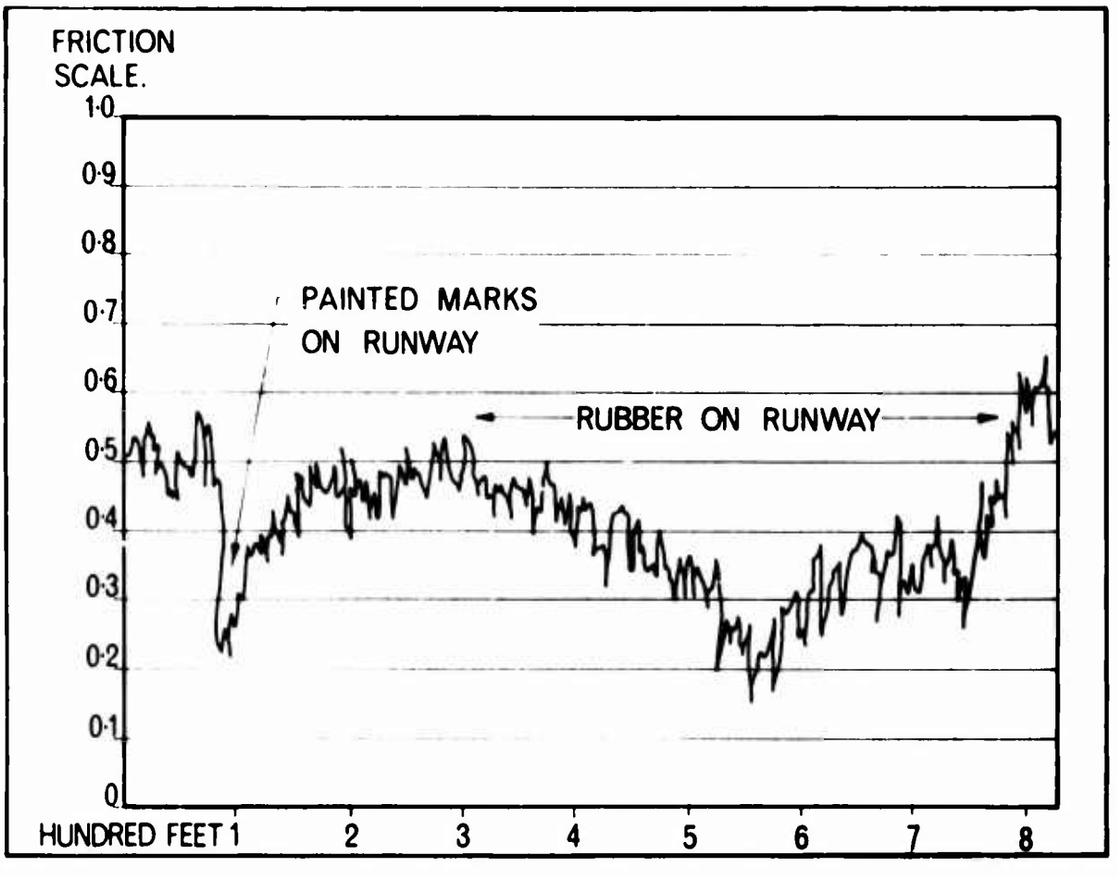


Figure D4.- Part of friction meter record showing rubber deposits in touchdown area.

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